plate is wiped clear by the stylus. The outline or boundary of this area represents the maximum and minimum load factors experienced throughout the range of speed flown, and with the use of Equation (2), the lift coefficient may be found at any point.

If the load factors recorded have been caused by gusts, which is invariably true of the larger values on transport airplanes in normal operations, the V-G record also provides the means for determining, through the medium of Equation (1), the fictitious gust velocities U corresponding to the simple sharp-edged-gust assumption. The outline of the V-G area, therefore, may be converted into a plot against speed of the maximum gust velocities encountered during the period of operation.

From the statistical standpoint, the V-G recorder leaves something to be desired since it gives no clue to the frequency distribution of the gust intensity on which a statistical analysis would be made. On the other hand, because of its simplicity and mode of operation, the instrument can be handled satisfactorily by unskilled personnel with a minimum of instruction, thus permitting a relatively large amount of data to be obtained on a wide front. Moreover, the records tell their story at a glance and require very little analysis. The instrument therefore amply justifies itself.

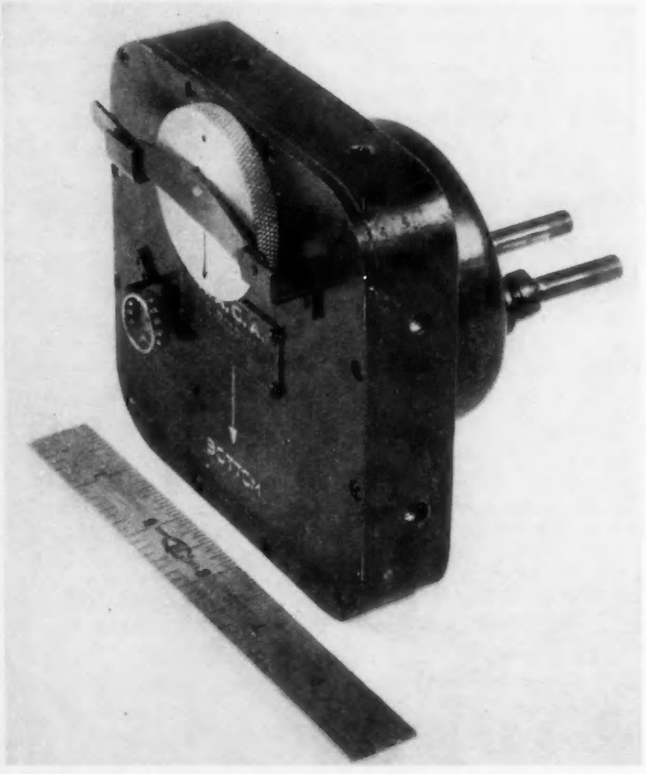

Fig. 1 – V-G Recorder

Table 1 – Scope of V-G Measurements (Transport Airplanes)

Airplane Type	Airline	Total Hours Flown	Routes Flown
Boeing 247	United	6907	Whole system—coast to coast. Seattle—Oakland—New York City.
Boeing 247-D	United	4535	Whole system—coast to coast. Seattle—Oakland—New York City.
Douglas DC-2	TWA	1066	Whole system—coast to coast. New York—Los Angeles, Calif.
Douglas DC-2	Pan-American Grace	533	Santiago, Chile,—Buenos Aires, Argentine.
Douglas DC-2	Eastern	655	Miami, Fla.—New York City.
Sikorsky S-42	Pan-American Grace	500	Miami, Fla.—Buenos Aires, Argentine.
Sikorsky S-42A	Pan-American Grace	1210	Miami, Fla.—Buenos Aires, Argentine.
Sikorsky S-43	Pan-American Grace	140	Miami, Fla.—Cristobal, Canal Zone.
Martin 130	Pan-American	1440	Alameda, Calif.—Manila, P. I.
Ford 5AT-C	Pan-American Grace	2771	Santiago, Chile—Buenos Aires, Argentine.
Fairchild FC-2W2	Pan-American Grace	307	Santiago, Chile—Buenos Aires, Argentine.
Fokker F10-A	American	300	Dallas, Tex.—Cleveland, Ohio.
		20,364	

Scope of Measurements. – The scope of the V-G measurements is described in terms of type of airplane, number of flying hours of record for each type, routes flown, and seasonal distribution of flying time. This information is given in Table 1 and Fig. 2. The data presented, to which this information applies, include all of the useful data obtained on commercial transport airplanes to October, 1936. In addition to these data, two records that are of special interest because of the high gust values involved are included.

Composite $U_{max.}$ Diagrams. – Space limitations prevent, in a paper of this character, a presentation of the numerous individual V-G records obtained or even of composite V-G diagrams for each airplane type. Such a presentation, moreover, would mean very little, as the variations in the conditions and periods of time in which the various airplanes were flown make abortive any attempt at this time to define a precise experimental interdependence among effective gust intensity, airplane speed, size, and wing loading.

With the exception of a few special cases, therefore, the complete data are presented in Fig. 3 in the form of composite diagrams of gust velocity plotted against a speed ratio. The gust velocities, $U_{max.}$, have been determined from the individual V-G diagrams in the manner previously described; the speed ratio V/V_L is the ratio of the indicated speed at which the gust was encountered to the maximum indicated speed of the airplane in level flight. In evaluating $U_{max.}$, the gross weights of the airplanes were used because of the lack of knowledge of the actual weights at the times when the most severe gusts were encountered, and also because this procedure yields conservative values of U. The weights and other pertinent characteristics of the airplanes represented are given in Table 2.

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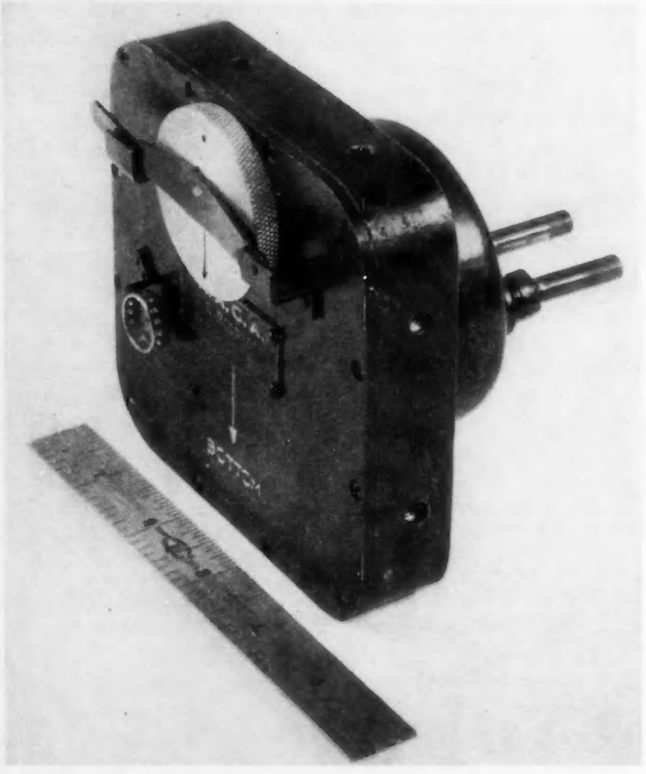

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In Fig. 3 data on the land transports have been separated from the data on the large flying boats. This separation is desirable because of certain large differences between these two groups of airplanes, namely, (1) in operating conditions, (2) in size of airplanes, (3) in wing loading, and (4) in flying time recorded.

It will be noted upon inspection of Fig. 3 that, in the case of the land transports, the effective gust velocities are roughly the same at all values of V/V_L between 0.5 and 1.0, above which they rapidly decrease to zero at a V/V_L of about 1.3, the maximum speed ratio recorded. The diagram is more or less symmetrical, indicating an equal distribution of positive (upward) and negative (downward) gust loads from the 1 g datum. The gust values are for the most part surprisingly close to the value of 30 ft. per sec. originally selected for design purposes, and they do not exceed about 35 ft. per sec. Considering the scope of the data, this result

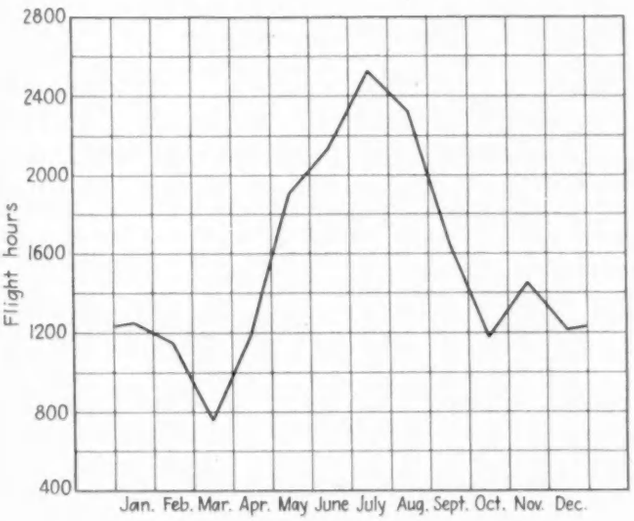


Fig. 2 – Seasonal Distribution of V-G Flying Time for 1936

is a rather good proof of the soundness of the present design assumptions as applied to the common transport airplanes.

The tapering off of the gust values above the maximum speed indicates that the airplanes fly such a small part of the total flying time above this speed that they have not yet encountered the larger gusts in this range. If we consider the frequency distribution of gust intensity, such as that shown from some early measurements in Fig. 4, we find that gusts of the largest intensity are normally encountered only once

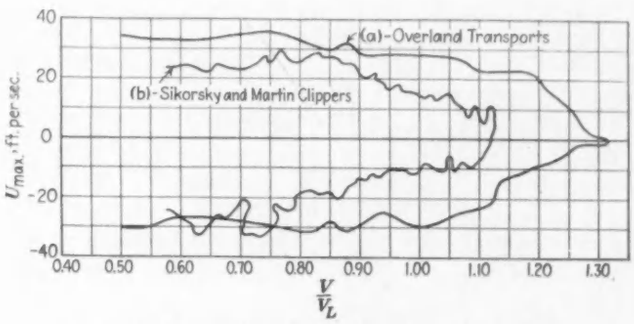


Fig. 3 – Effective Gust Velocities from V-G Records

or twice per 1000 hr. or more of flying, so that the chances of encountering these gusts during the few particular times that the airplanes exceed maximum speed are extremely remote.

In the case of the large flying boats, the diagram is similar to that for the smaller land transports. The gust values start tapering off noticeably above a V/V_L value of about 0.85 on the positive side and above about 0.75 on the negative side. This result indicates that the large boats are flown at speeds greater than cruising speed to a much lesser extent than are the land transports. It will also be noted that the maximum speed flown on the boats is only about 1.1 V_L as compared with the value of 1.3 for the land transports.

The most noteworthy feature of the results shown on Fig. 3, taken in conjunction with the flying times listed in Table 1, is the closeness with which the maximum gust values for the boats are approaching (even exceeding on the negative side) the values for the land transports, notwithstanding the much smaller total flying time represented on the boat records, and also notwithstanding the differences in operating conditions on the two types. Unfortunately, because of the character of the data, no definite conclusions can be drawn from this result, but certain inferences may be justified at the present time.

For example, it appears from the rate of growth of the maximum gust values on the large boats that, by the time as many data are obtained on this type as we now have on the land transports, the gust values for the boats may generally exceed those measured to date on the land types. If this relation occurs, it will occur in spite of the differences in operating conditions between the boats and the land transports, which differences should, other things being equal, result in lower gust values for the boats.

Quoting from a competent authority, "The long-range flight from Alameda to Honolulu is made at night, and it is sometimes necessary to fly through small squalls and cold fronts;

Table 2 – Airplane Characteristics

Airplane	Gross Weight, lb.	W/S, lb. per sq. ft.	W/P, lb. per hp.	V_L, Indicated, m.p.h.	Altitude at V_L, ft.	$\frac{V_{(V\text{-}G)}}{V_L}$	Source of Data
Boeing 247	13,100	15.67	12.48	169	5000	1.23	Boeing Aircraft Co.
Boeing 247-D	13,650	16.32	12.41	177.5	8000	1.32	Boeing Aircraft Co.
Douglas DC-2	18,200	19.4	12.2	215	8000	1.01	Douglas Aircraft Co.
Sikorsky S-42	40,000	29.9	13.4	171	7000	1.00	Sikorsky Aircraft Division, United Aircraft Mfg. Corp.
Sikorsky S-42A	40,000	29.9	13.3	171	7000	1.05	*Aviation*, March, 1936.
Sikorsky S-43	19,000	24.3	12.7	175	7000	1.06	*Aviation*, March, 1936.
Martin 130	52,000	22.9	15.65	160	8000	1.08	Glenn L. Martin Co.
Ford 5AT-C	14,000	16.8	11.0	148	Sea Level	1.27	Ford Motor Co.
Fairchild FC-2W2	4,500	13.4	10.6	137	Sea Level	1.21	N. A. C. A.
Fokker F10-A	13,100	15.4	10.9	140	Sea Level	1.08	*Aviation*, August, 1929.

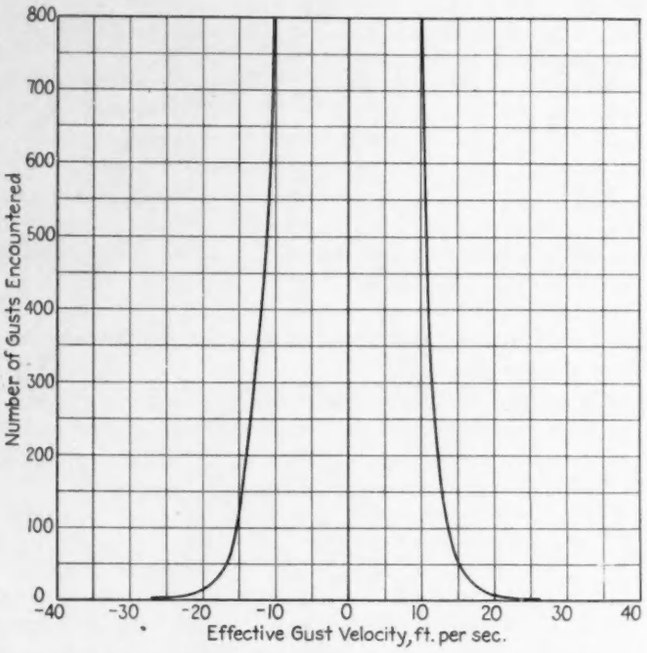


Fig. 4 – Frequency Distribution of Gust Intensity during 1320 Hr.

however, there is a considerable amount of shipping in this area and meteorological forecasts are quite good. With this information, courses are usually plotted and flown which avoid all areas where high gust velocities are likely to occur. Although the meteorological information west of Honolulu is relatively meager, all these flights are made during daylight and the operating personnel make every effort to avoid squalls and dangerous weather. In the rare instances when they are forced to fly through squalls, they usually descend to 100 ft. to do contact flying." In other words, in contrast to the land transports, the boats are operated under conditions that permit considerable latitude in route, both horizontally and vertically, so that squally or storm areas can be avoided to a greater extent. Furthermore, over water many of the conditions that are favorable to turbulence in the atmosphere are lacking – for example, insolation, which causes gusts due to instability, and friction near the ground, particularly over rough country, which causes very strong gusts due to mechanical action.

From arguments such as the foregoing, we would anticipate considerably smaller gust values for the boats than for the overland transports, and the fact that we are not getting them should be regarded as significant. A clue to the possible reasons for this unexpected result may be found in the following brief review of some data on gust gradients in conjunction with an elementary consideration of the behavior of airplanes of different size and wing loading in different types of gust.

Effect of Gust Gradient

Theoretical Considerations. – The theoretical curves given are based on Küssner's[3] Equation (14). This equation expresses the ratio of the "true" acceleration in vertical gusts to the acceleration computed from the usual sharp-edged-gust assumption. The "true" acceleration is circumscribed by the following conditions:

(1) The unsteady flow with sudden changes in angle of attack, (Wagner effect[4]), is taken into account within the limitations that:

(2) The flow is two-dimensional.

(3) The pitching motion is neglected.

(4) The wings are rigid.

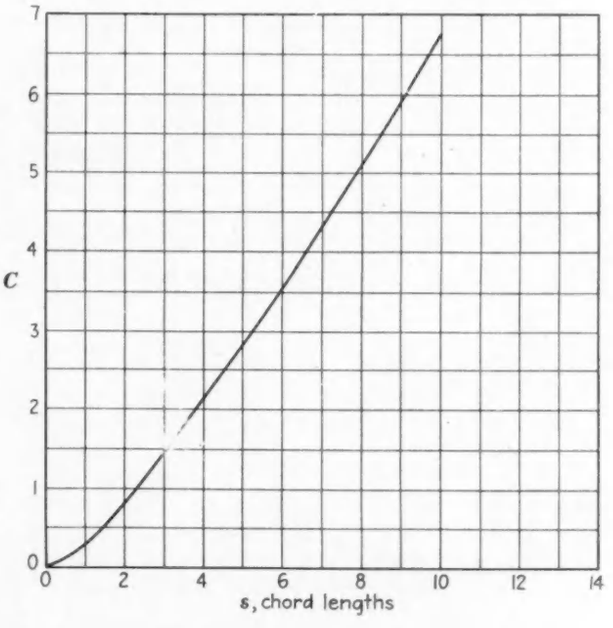


Fig. 6 – Relation between C and s

For the present purpose, Küssner's equation has been solved for two simple gust forms: (a) the sharp-edged gust, and (b) the gust with linear gradient. In the latter case the solution given here is limited to the action between the beginning of the gust and the point at which the maximum gust velocity occurs, which is the point of maximum acceleration throughout a wide range of gust gradients.

The solutions of Küssner's equation are:

(a) For the sharp-edged gust:

$$\frac{\Delta n_t}{\Delta n_s} = \eta_o - \frac{2}{2M + s} C \qquad (3)$$

[3] See N.A.C.A. Technical Memorandum No. 654, January, 1932; "Stresses Produced in Airplane Wings by Gusts," by H. G. Küssner.

[4] See *Zeitschrift für Angewandte Mathematik und Mechanik*, Vol. 5, February, 1925, pp. 17-35; "Uber die Enstehung des dynamischen Auftriebes von Tragflügeln," by Herbert Wagner.

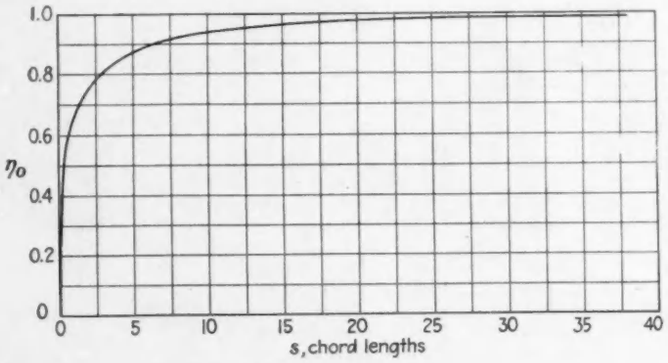


Fig. 5 – Relation between η and s

(b) For the gradient gust:

$$\frac{\Delta n_t}{\Delta n_s} = \frac{1}{s_o}\left[A - \frac{2}{2M + s} B\right] \qquad (4)$$

in which Δn_t is the "true" acceleration,

Δn_s, the acceleration computed from the usual sharp-edged-gust assumption for a gust velocity equal to the maximum of the gust for which Δn_t is determined,

τ_{10}, coefficient of unsteady lift (see Fig. 5),

$M = \dfrac{2W}{g \rho a S c} + \frac{1}{4}$

a, slope of wing-lift curve per radian,

W, g, ρ, S, c, standard symbols.

s, distance from "edge" of gust to point at which acceleration is computed, chord lengths,

C, function of s (see Fig. 6),

s_o, distance at which gust reaches maximum, chord lengths,

A, function of s (see Fig. 7),

B, function of s (see Fig. 8).

It will be noted that the acceleration ratio is dependent on the wing loading, chord, and slope of the lift curve. In order to show the significance of the equations as briefly as possible in a graphical manner, the maximum acceleration ratios occurring in the gusts selected have been plotted against wing loading with the chord as parameter in Figs. 9, 10, and 11. The slope of the lift curve used in the computations is 4.5, which value represents a wing with an aspect ratio of about 7. It should be borne in mind that the dependent variable is an acceleration ratio, not an acceleration, so that the effect of the wing loading is to be interpreted in relation to its effect under the sharp-edged-gust assumption. For example, in all three gust gradients represented, it will be noticed that the acceleration ratio decreases with decreasing wing loading. Physically interpreted, this decrease occurs because airplanes with the lighter wing loadings respond more freely to the gust so that they acquire a greater vertical velocity in the gust direction, thereby resulting in a greater alleviation of load. In fact, the acceleration ratio is frequently referred to in effect as an alleviation factor to be applied to the sharp-edged-gust formula. The effect of the chord length is important only in the gusts with very steep gradient and, with the distance H equal to 400 ft., it is very small, except at the lower wing loadings.

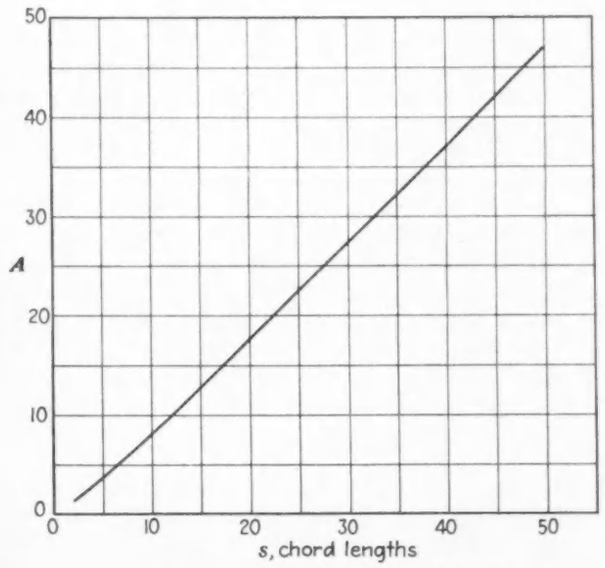


Fig. 7 – Relation between A and s

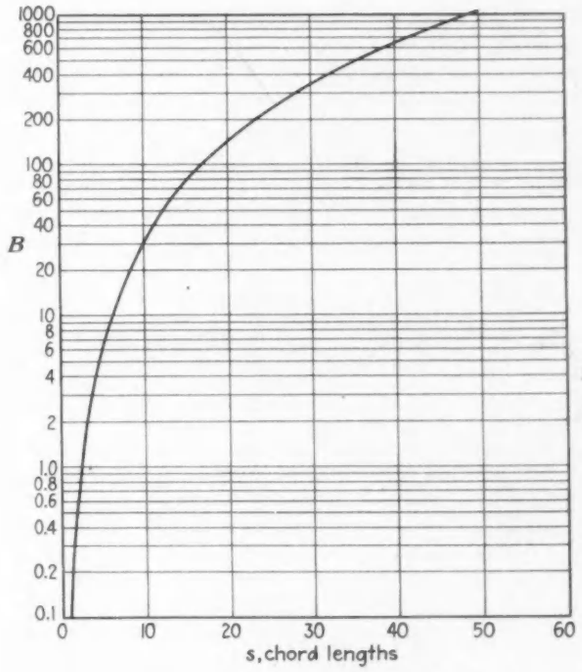


Fig. 8 – Relation between B and s

In order to get a more general picture of these effects on different sizes of airplanes, results have been computed on the basis of the mean relation between chord and wing loading shown in Fig. 12. The results are shown in Fig. 13. Again, maximum values of the acceleration ratio have been plotted against wing loading, but with the distance H now as parameter. In the case of the sharp-edged gust, $H = o$, the acceleration ratio is virtually constant between wing loadings of 5 and 30 lb. per sq. ft. Thus, if the gusts encountered by airplanes actually had infinite gradients, the simple sharp-edged-gust formula, as currently used to interpret acceleration data, would lead, on the whole, to a reasonably correct application of the data to airplanes with size and wing loading different from those of the airplanes on which the measurements were made. This point is fairly obvious but may be made clearer by a simple example:

Suppose an acceleration increment of 3 g were measured at a speed of 300 ft. per sec. on an airplane whose wing loading was 15 lb. per sq. ft. and whose lift-curve slope was 4.5. The effective gust velocity from these data as calculated from equation (1) is

$U_e = 28$ ft. per sec.

But since, from Fig. 13, the acceleration ratio for the infinite gradient is 0.71, the true gust velocity that caused the acceleration of 3 g must have been $\frac{28}{0.71}$ or 39.5 ft. per sec. Now, suppose we want to apply the measured data to an airplane with twice the wing loading. Under the same conditions of speed and lift-curve slope, and with $U_e = 28$ ft. per. sec., Equation (1) says that the acceleration increment will be 1.5 g, or half the value measured originally. The same result is now obviously obtained by calculating the acceleration from

Equation (1) using the true gust velocity of 39.5 ft. per sec. and reducing it by the factor 0.71.

In the case of gusts with finite gradients the acceleration ratio is not constant but decreases with the wing loading. If the gusts encountered by airplanes have mild gradients, say $H > 100$ ft., the use of Equation (1) in applying the measured data to airplanes of different size and wing loading leads to reasonably small error only within a very narrow range of these characteristics. In the example just cited, if H were 300 ft., the effective gust velocity based on the original measurements would remain 28 ft. per sec., but the true gust velocity would now be $\frac{28}{0.42}$ or 67 ft. per sec. Applying the measured data through Equation (1) to the airplane with the wing loading of 30 lb. per sq. ft. would still result in an acceleration of 1.5, but the true acceleration would be

$$3 \times \frac{15}{30} \times \frac{67}{28} \times 0.56 = 2.0\,g$$

which is an increase of about 33 per cent. We therefore see that, with finite gust gradients, the use of the simple sharp-edged-gust formula leads to unconservative estimates of the gust loads on large, heavily loaded airplanes. Conversely, it leads to over-conservative estimates for small, lightly loaded airplanes. A knowledge of the actual gradients of the stronger gust is therefore essential in order that acceleration data may be properly applied to design.

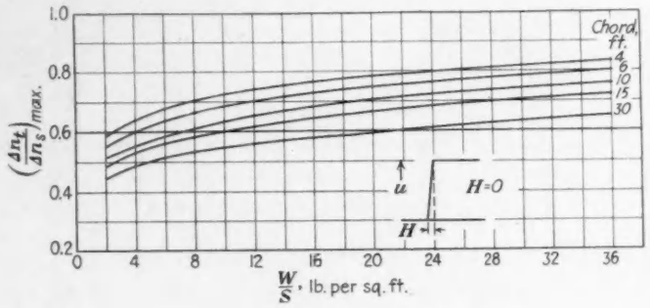


Fig. 9 – $H = 0$

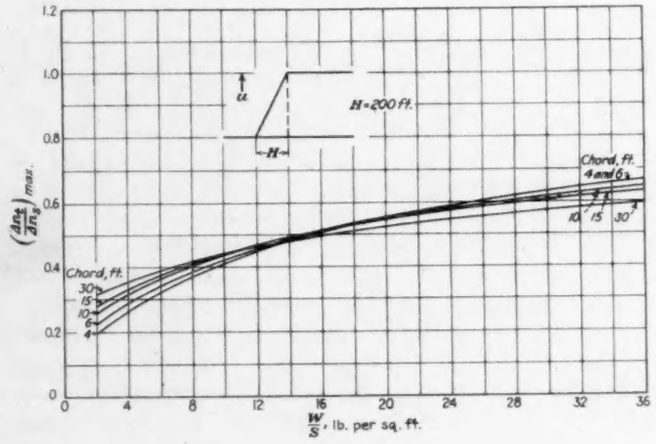


Fig. 10 – $H = 200$ Ft.

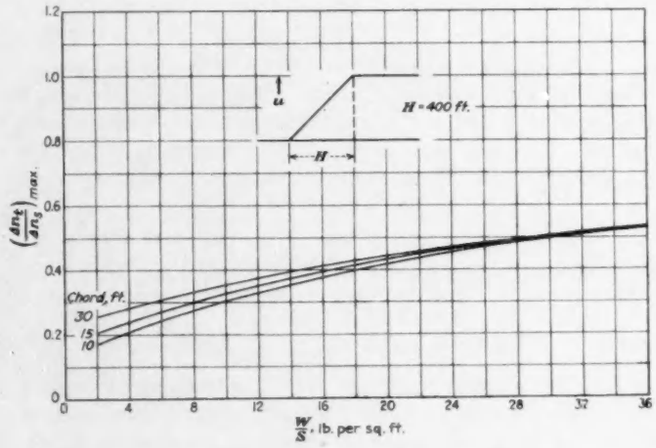


Fig. 11 – $H = 400$ Ft.

Figs. 9, 10, and 11 – Effect of Wing Loading and Chord on Acceleration Ratio

Experimental Data. – Although the program is not yet completed, the National Advisory Committee for Aeronautics has obtained some data on the relation between gust intensity and gradient that indicate that the stronger gusts have relatively mild gradients. These data were obtained by measurements of the motion of small airplanes in gusts and by interpreting the results with due allowance for the Wagner effect.[4] The results from the first set of measurements, which include some 1000 individual gusts of the type that derive their energy from the wind, are shown in Fig. 14. The broken curve represents the upper limit of the data.

The trend of the data indicates not only that the distance to the peak of the gust increases with increasing gust intensity, but also that the gradient, $\frac{dU}{dH}$, actually decreases. The curve can be extrapolated on the basis of certain reasonable-looking assumptions to give an idea of the gradients or H values corresponding to stronger gusts beyond the limit of the data.

To perform this extrapolation, let us assume that each particle or small unit volume of air contains, at a given isobaric level, the same amount of energy as do all other similar unit volumes at the same level within the sphere of action. Now if, under the action of some more or less general influence associated with the weather conditions in force, these unit volumes are caused to transform their energy into turbulent energy, each at the same rate at any instant, each gust will receive an amount of energy at a rate approximately proportional to the total volume of air involved in the gust. The power available for each gust under these conditions is therefore approximately proportional to H^3. Such a state of affairs could only be transitory as the energy transferred to the gusts would be, in turn, transformed into some other form of energy until a condition of equilibrium was attained, when the atmosphere would become quiescent.

Now in any unidirectional gust of a given shape, the power of the gust is proportional to the cube of the velocity and to the cross-sectional area through the gust, namely, $P \propto U^3 H^2$. We have, then, equating the instantaneous power available to the instantaneous power of the gust:

$$U^3 H^2 \propto H^3$$
$$\text{or} \quad U^3 \propto H$$

If we choose a constant of proportionality such that this cubic parabola passes through the uppermost point of our data, the curve of Fig. 15 is obtained which, it will be noted, follows the data reasonably well.

Various similar parabolas could be drawn, each representing a given condition of power available from the atmosphere, and the parabola of Fig. 15 simply corresponds to the power available under the roughest conditions that we have measured.

With the extrapolated relationship thus derived for the particular conditions of our data, the higher gust velocities, namely, those of the order of 40 to 50 ft. per sec., are found to be developed in distances of the order of 200 to 350 ft.

Effect on U_{max} Diagram. – If it is now assumed that the gradient distance H is, say, 300 ft., for the purpose of recalculating the effective gust velocities from the V-G records, and if this recalculation is performed on the basis of Equation (4), the U_{max} diagram of Fig. 16 is obtained. Although the gust values have been increased considerably, the new values are by no means impossible ones. The important point to note is that the maximum values from the boats are now appreciably less than those from the land transports, a result

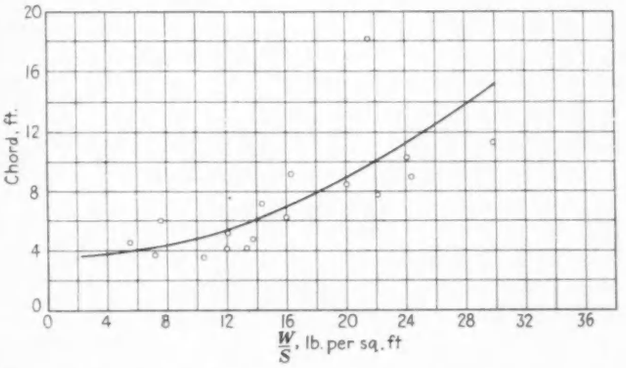


Fig. 12 – Relation between Chord and Wing Loading for a Number of American Airplanes (Data from *Aviation*)

that appears more reasonable, in the light of the previously discussed difference in flying time and operating conditions between the two types, than the result shown in Fig. 3.

Unique V-G Records

Although some concluding remarks are reserved on the effect of the gust gradient on the load factors, two V-G records remarkable for the high gust values involved will now be discussed. These records have not been included in the previous data or discussion because it has not been felt that they applied or should apply to normal transport operation, although one of them actually was obtained on a transport airplane on a scheduled flight.

The first of these records, Fig. 17, was obtained on a Lockheed "Orion" piloted by Maj. James H. Doolittle, and the strong gusts were encountered about noon of Dec. 5, 1932. The airplane was "flying very low into the teeth of a 35 m.p.h. headwind" over the western foothills of the Ozark Mountains in Oklahoma. The limited weather data for the day at the locale of the gusts indicate that the temperature-lapse rate was sub-adiabatic, or stable, but that the wind gradient near the ground was probably very strong. Under these conditions, strong turbulence would be expected near the ground, particularly over rough country, but probably not at the greater heights. The statement of the pilot that he was "flying very low" therefore accounts for the fact that rough air was encountered.

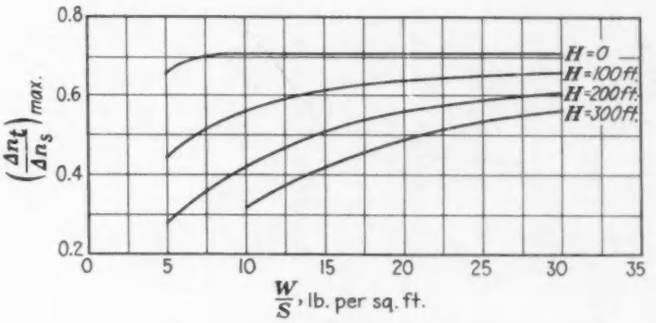


Fig. 13 – Effect of Gust Gradient and Wing Loading on Acceleration

The record indicates that several upward accelerations of the order of 4 g were experienced, with one value of 5.2 g occurring at 195 m.p.h. The effective gust velocity, based on the actual weight at the time of the record, was 47 ft. per. sec. On the basis of gross weight, the effective gust velocity was 51 ft. per sec., which is the value that should be compared with those shown on Fig. 3.

The second of these records, Fig. 18, was taken on a DC-2 airplane of Eastern Airlines. The strong gusts were encountered on the afternoon of June 11, 1936, between Richmond, Va., and Washington, D. C. Although special comment on V-G records is seldom received from the transport companies, in this case it was reported that the airplane encountered unusually rough air in an electrical storm at the time and location noted. Weather maps for the day show a cold front accompanied by squalls and thunderstorms between Richmond and Washington during the afternoon and evening – a typical line-squall situation.

The pilot of the airplane described the flight as follows: "The storm was encountered at about 2000 ft. We were in a descent with the intention of passing under the black front. As I recall, we were proceeding at about 3000 ft. when this line squall showed up in front. I started a descent intending to go under the clouds. There was considerable up-draft at the front of the squall, making it difficult to lose altitude

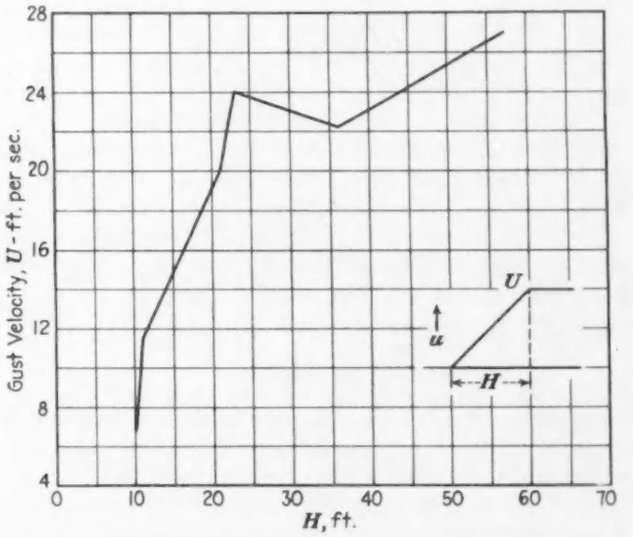


Fig. 14 – Relation between Gust Intensity and Spatial Dimension

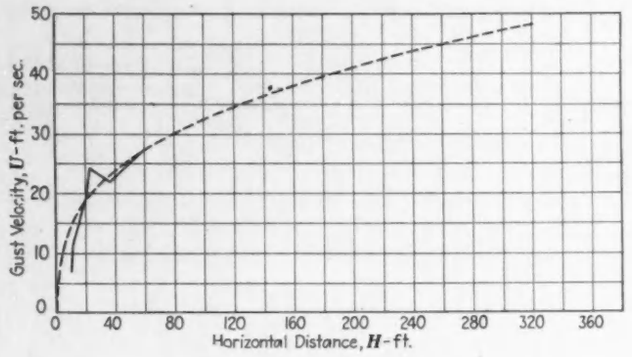


Fig. 15 – Relation between Gust Velocity and Spatial Dimension – Extrapolated

at cruising speed. I reduced the power and, as I entered the storm area, the air became so rough that it was necessary to pull all power and go into low pitch.

"There were down gusts of great violence along with some up-drafts. They were severe enough to throw a passenger out of his seat, up toward the top of the cabin. It was necessary to descend to approximately 1000 ft. before the turbulence abated sufficiently to proceed.

"I consider that the airplane was subjected to unusually severe roughness on this flight. It was much rougher than I had anticipated."

It will be noted, from Fig. 18, that the V-G record verifies

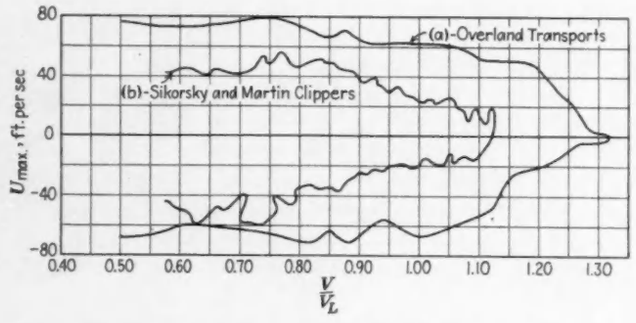


Fig. 16 – Gust Velocities from V-G Records Based on Gradient Gust, $H = 300$ Ft.

the pilot's statement concerning the violent downward gusts. The maximum acceleration is about $-2.5\,g$ ($-3.5\,g$ from the $+1\,g$ datum) and it occurred at a speed of between 185 and 190 m.p.h. This value corresponds, on the basis of gross weight, to an effective gust velocity of -47 ft. per sec. The maximum upward acceleration was $3.5\,g$ (an increment of $2.5\,g$), and corresponds to an effective gust velocity of $+33$ ft. per sec., a not unusual value.

Conclusions

The gust-gradient data shown in Fig. 14, used in conjunction with the theoretical consideration of the Wagner effect and the effect of gust gradient on the vertical motion of airplanes of different size and wing loading, were seen to have a qualitative influence on the interpretation of the V-G records, and this influence is of such a character as to cause a more reasonable relationship between V-G data from two widely different groups of airplanes. It may be inferred from this result that the important gusts encountered by airplanes under normal transport-operating conditions do not have very sharp gradients, and that the present design assumption of a sharp-edged gust as applied according to the laws of steady flow should perhaps be modified to allow properly for the effect of the gust gradient. The result of such a modification would be to reduce the gust-load requirements on small, lightly loaded airplanes and to increase them on large, heavily loaded airplanes without affecting the specified loads for the "average" transport types currently in use on the domestic airlines. Quantitatively, such a modification would be difficult to make at this time, as the actual gust gradients have not been very well established. This difficulty,

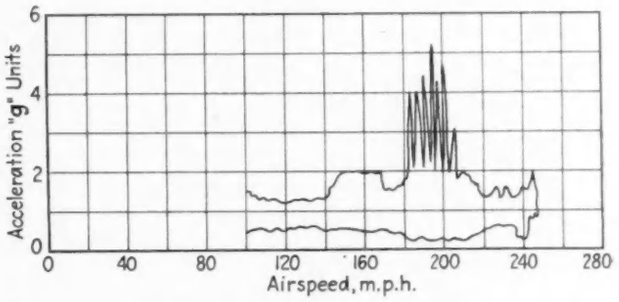


Fig. 17 – V-G Record for Lockheed Orion in Severe Gusts

however, should not prevent the use of good judgment in selecting design load factors.

In view of the fact that the effective gust velocities derived from two records exceed current minimum gust requirements by from 60 to 70 per cent, it appears that excessive gust loads may be applied under certain extreme conditions. From the standpoint of transport operations, the most important of these conditions is the severe thunderstorm or line squall. It would seem that such conditions should be avoided by the operators, as it may become impracticable to design the larger airplanes for the strongest gusts likely to be encountered in severe storms.

In conclusion, acknowledgments should be made to the numerous persons contributing to the material that forms the basis of this paper. In particular, acknowledgment is due Walter F. Burke of the staff of the National Advisory Committee for Aeronautics, for having performed the solutions of Küssner's equation, and to Walter G. Walker, also of the Committee's staff, for having done most of the routine work in connection with the V-G records.

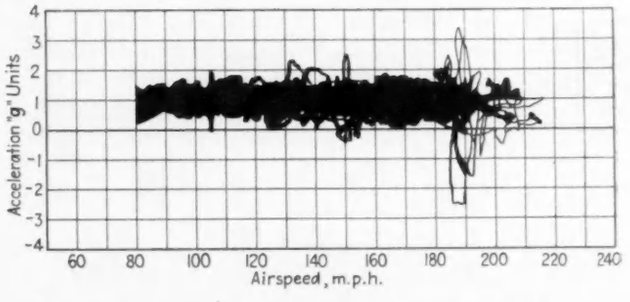


Fig. 18 – V-G Record for DC-2 Transport in Line Squall

Observations on Cylinder-Bore Wear

By Max M. Roensch
Chrysler Corp.

IN analyzing causes of cylinder-bore wear it is found that they fall generally into one of the following classifications:

(1) Abrasion – wear due to foreign particles in the oil film.
(2) Erosion – wear due to metal contact between the pistons or rings and the cylinder bore.
(3) Corrosion – oxidization or chemical action of the cylinder wall by the products of combustion.

Although these classifications place the three main factors in the approximate order of their importance, the conditions of operation, the design of the engine, the design of the air cleaner, the piston and ring equipment, or the lubricating oil used, may change the order completely.

Four ways are described for abrasives to get into the engine, and three design factors are mentioned that will reduce cylinder wear in the presence of dust. Keeping the dirt out, however, is stated to be the only real solution, and air cleaners are recommended as the best method.

Ample space is devoted to a discussion of erosion and corrosion with various causes and cures.

CYLINDER-BORE wear is just about in a class with politics and religion, for it is one of the most controversial subjects about which engineers can argue, the reason being that there is so little real fundamental engineering data available. This situation became evident when, in gathering material from the various members of the cooperative group appointed to collect data for this paper, member *A* said very positively, "We do not have cylinder-bore wear at high speeds and high loads," whereas member *B* said, "We have cylinder-bore wear only at high speeds and high loads." Both parties may not be absolutely correct, but both have data to prove their points on their own engine designs. The trouble is that, because there are so many variables involved in this problem, it is very difficult to hold all other conditions constant so that the effect of any one variation may be investigated. This difficulty was brought out very clearly in that excellent paper, "Cylinder Wear in Gasoline Engines," that was read before this group last year by C. G. Williams[1]. Due to this multiplicity of variables it should be understood clearly now that my paper can only hope to show the trends of attempts to eliminate bore wear.

Although you have seen similar charts before, it will be well to refresh your memory, so Fig. 1 shows the typical cylinder-bore-wear chart on a six-cylinder engine. It is apparent that the wear is practically all in the ring travel with the maximum wear under the top ring. The bore wear for average conditions seems to be about 0.001 in. per 10,000 miles but it may vary from 0.00022 in. per 10,000, which was the smallest actual wear figure submitted, to 0.010 in. per 10,000 miles. These figures show about 50 times as much bore wear in one case as in the other, giving some idea of the possible range encountered in more or less normal operating conditions. Since practically all the bore wear occurs in the ring travel, it would seem that the trouble could be eliminated by concentrating our efforts on the piston-rings themselves, or maybe even going so far as to eliminate them entirely, but to date no satisfactory solution for this suggestion has been developed, much to the relief of the piston-ring manufacturers.

However, although the condition can and is being improved by work on piston-rings, there are so many other factors contributing to the cylinder wear over which the rings have no control that the engine manufacturer has plenty of research to do on the problem before he can put the entire burden on the piston-ring engineer.

In analyzing causes of cylinder-bore wear, it is found that they will fall generally into one of the following classifications:

(1) Abrasion – wear due to foreign particles in the oil film.

(2) Erosion – wear due to metal contact between the pistons or rings and the cylinder bore.

(3) Corrosion – oxidization or chemical action on the cylinder walls, pistons, and piston-rings by the products of combustion.

Although these classifications place the three main factors in the approximate order of their importance, the conditions of operation, the design of the engine, the design of the air cleaner, the piston and ring equipment, or the lubricating oil used may change the order completely.

Abrasion

Abrasives may get into the engine in any one of the following ways:

(1) Core sand, cast-iron fillings, chips, and dirt may be

[This paper was presented at the Annual Meeting of the Society, Detroit, Mich., Jan. 13, 1937.]

[1]See S.A.E. TRANSACTIONS, May, 1936, pp. 191-196; "Cylinder Wear in Gasoline Engines," by C. G. Williams.

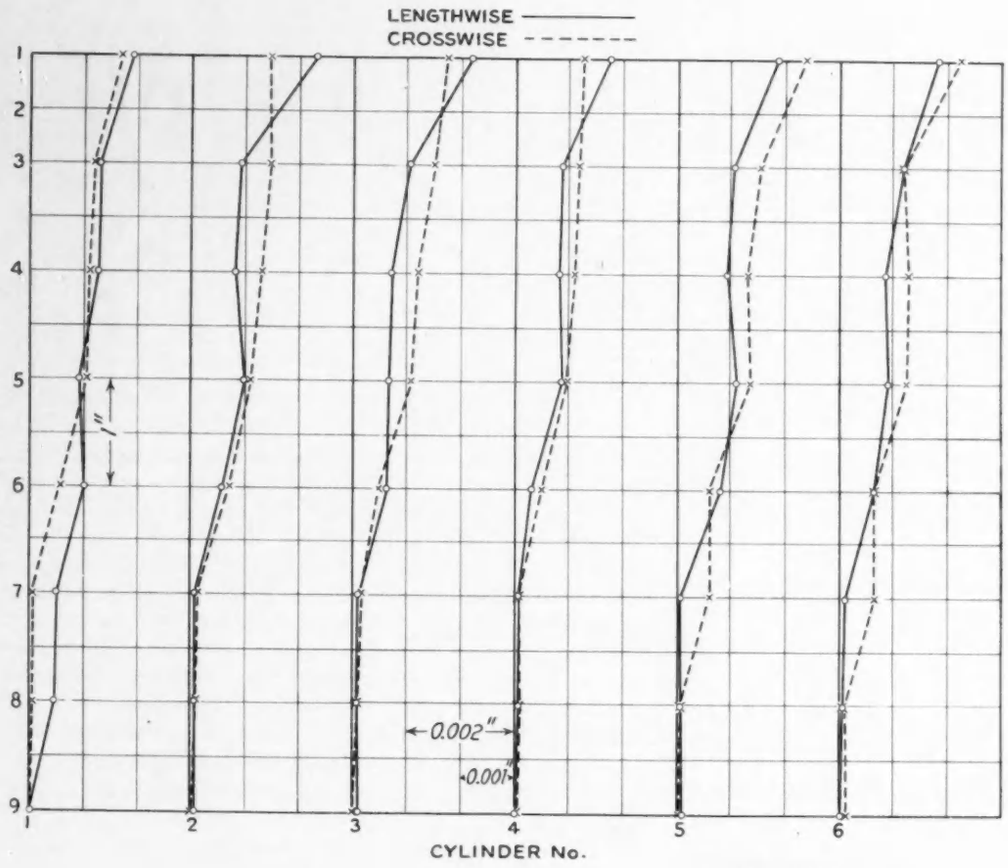


Fig. 1 (*left*) – Cylinder-Bore Wear after a 5000-Mile Trip through Dust Country on Air-Cleaner Test

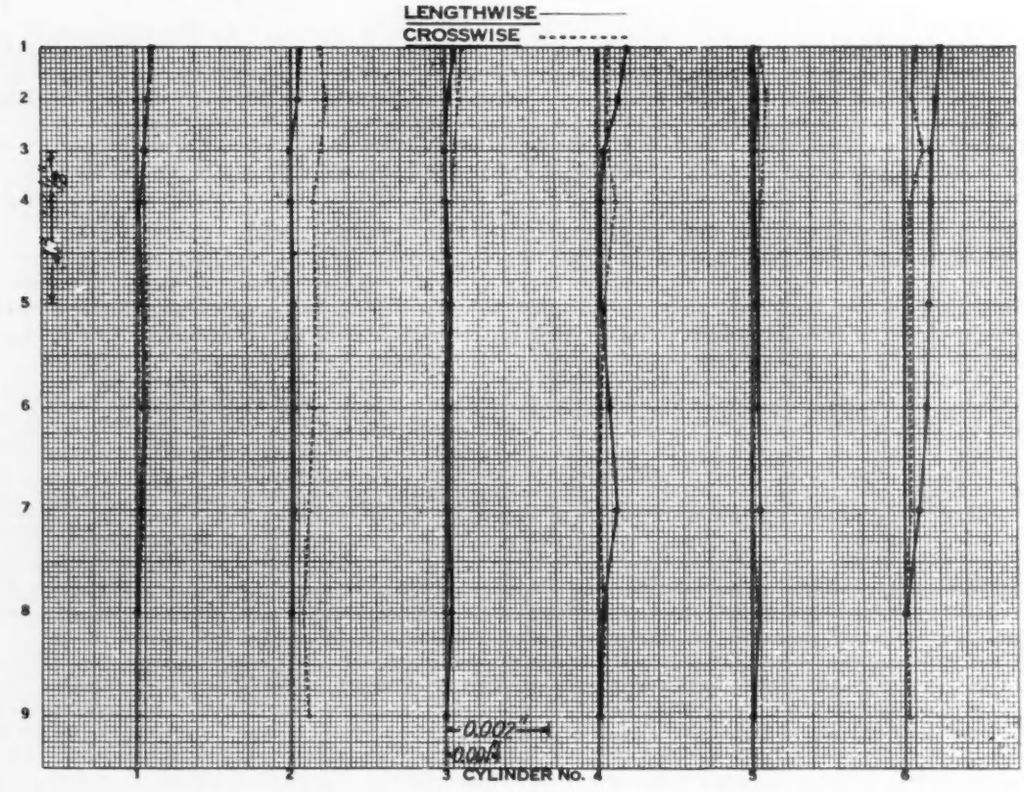
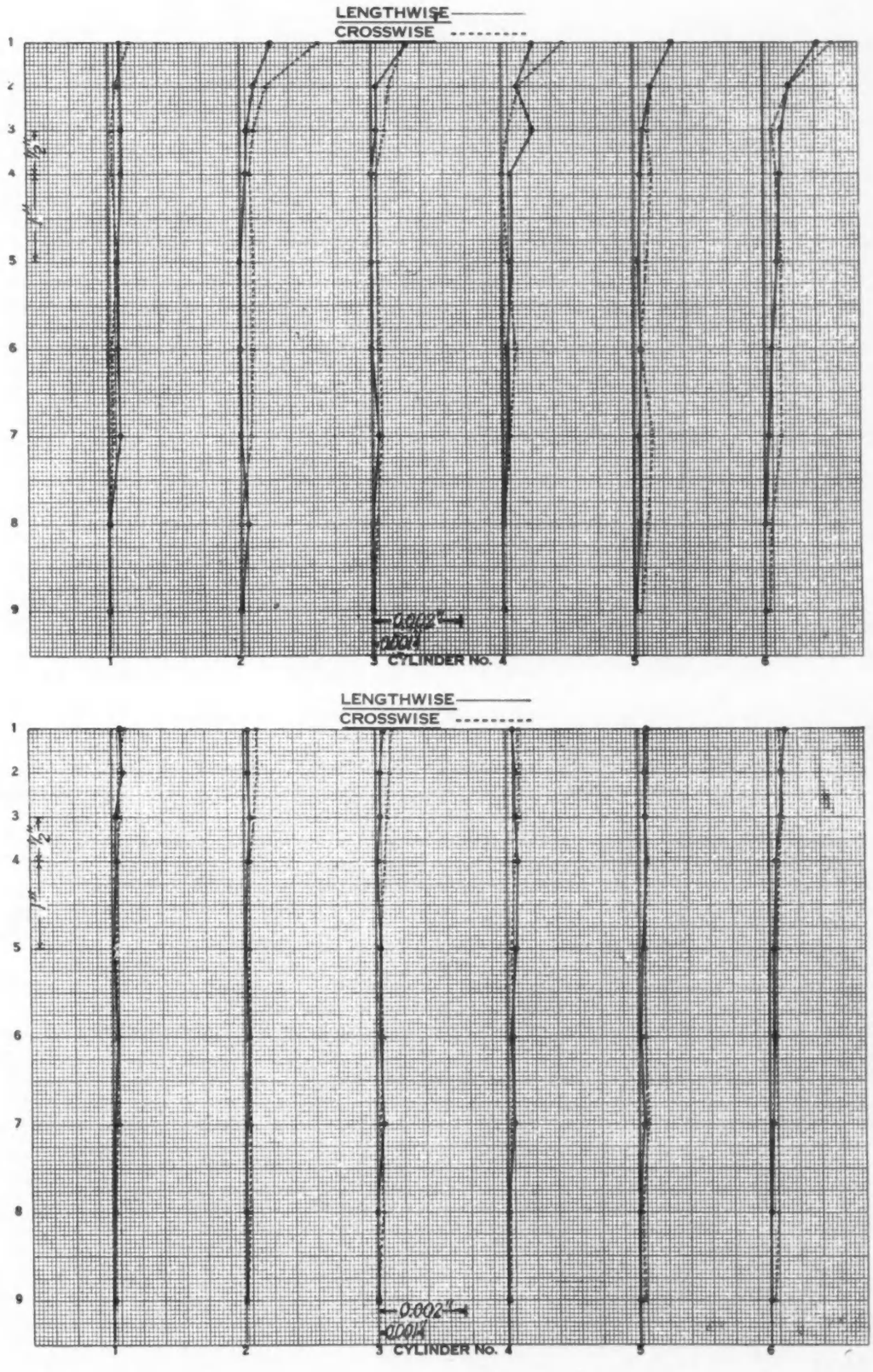


Fig. 2 (*right*) – Cylinder-Bore Wear after 10,000-Mile Transcontinental Trip – Road Car with Oil-Bath Cleaner

left in the engine and not taken out by the cleaning and washing processes. These substances get into the oil circulating system during engine operation.

(2) Valve-grinding compound or cylinder-honing residue may be left in the engine due to improper cleaning. This lack of care is more apt to happen in service than in production due to the elaborate cleaning processes used by all the manufacturers.

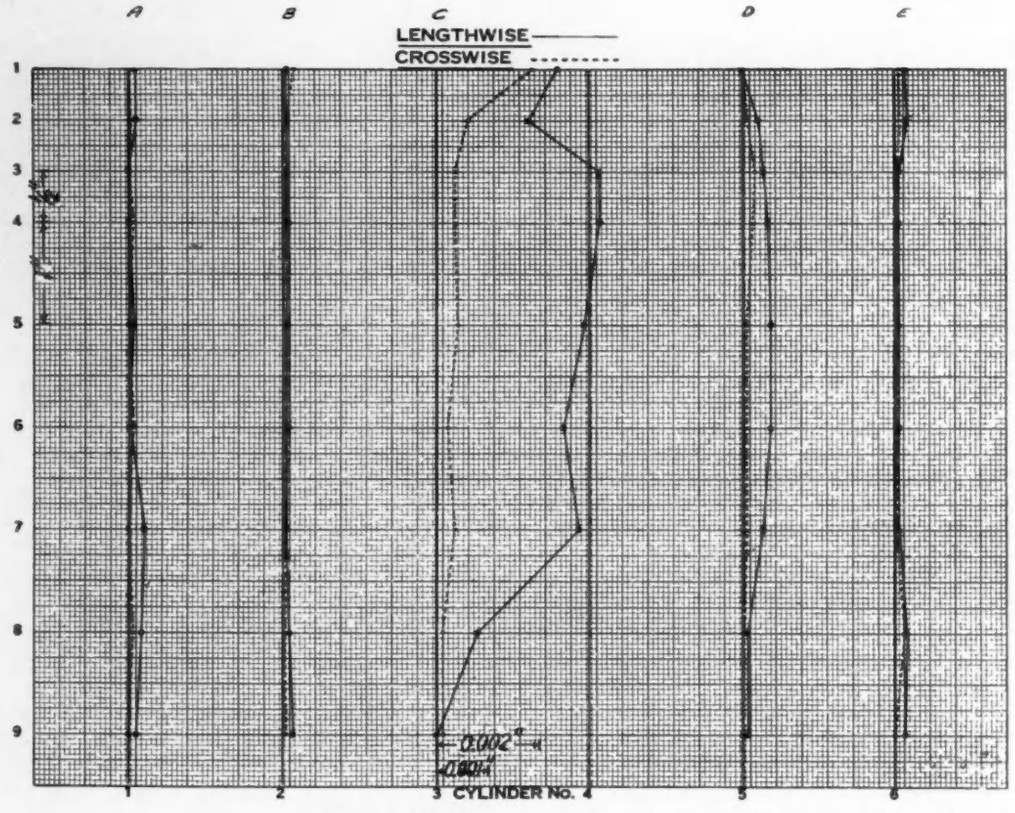


Figs. 3 and 4 – Cylinder-Bore Wear with Short Water Jacket (Fig. 3) and Long Water Jacket (Fig. 4) – 10,000-Mile Water-Brake Test

(3) Road dust may enter the crankcase with the ventilating air.

(4) Last, and most important, is the road dust that comes into the engine through the intake system. Dust has been the cause of more engine repair and replacement in service than almost any other single factor. Even with the improved air cleaners now generally used, dust entering the engine still causes more wear than most people suspect.

An automobile engine uses large quantities of air for the average car at 60 m.p.h., taking in 80 to 100 cu. ft. of air per min. and, even if the car is operating on a paved road, the air contains a considerable amount of dust in suspension



Figs. 5 (*left*) and 6 (*right*) – Average Cylinder-Bore Wear for All Six Cylinders

at all times so that there is nearly always some dust going into the engine. The last few years have seen extreme conditions, and many will recall the mud showers we had last summer, the result of excessive dust in the air being washed down by a rain storm. With cars operating on paved roads without effective air cleaners, we have been able to detect the effect of the dust content in the air on cylinder wear, as the wear is about 25 per cent lower in winter than in summer.

The almost universal adoption of the oil-bath air cleaner has been the greatest step forward in reducing the dust evil. These new cleaners are 95 to 97 per cent efficient over a wide range of air flow, but it must be remembered that under severe dust conditions even as little as 5 per cent of the dust going into the engine will still cause abnormal wear.

The effect of this dust is illustrated clearly by comparing Fig. 1, which shows the wear on a test car in the Southwest using a copper wool-filled cleaner as compared to a similar car operating with an oil-bath type, Fig. 2. The average wear shown in Fig. 1 is 0.002 in. in 5000 miles. Fig. 2 shows how little wear occurs without dust as the wear is only 0.0005 in. for 10,000 miles – a ratio of 8 : 1. Dust that is carried in with the intake air is very destructive as it goes directly on to the cylinder walls, mixes with the oil, and wears the piston-rings and bores at the next stroke of the engine.

The following are factors in the design and construction of the engine that may reduce cylinder wear in the presence of dust:

(1) Cylinder-block hardness and alloy content.
(2) Piston-ring line-up and ring design.
(3) Piston material and design.

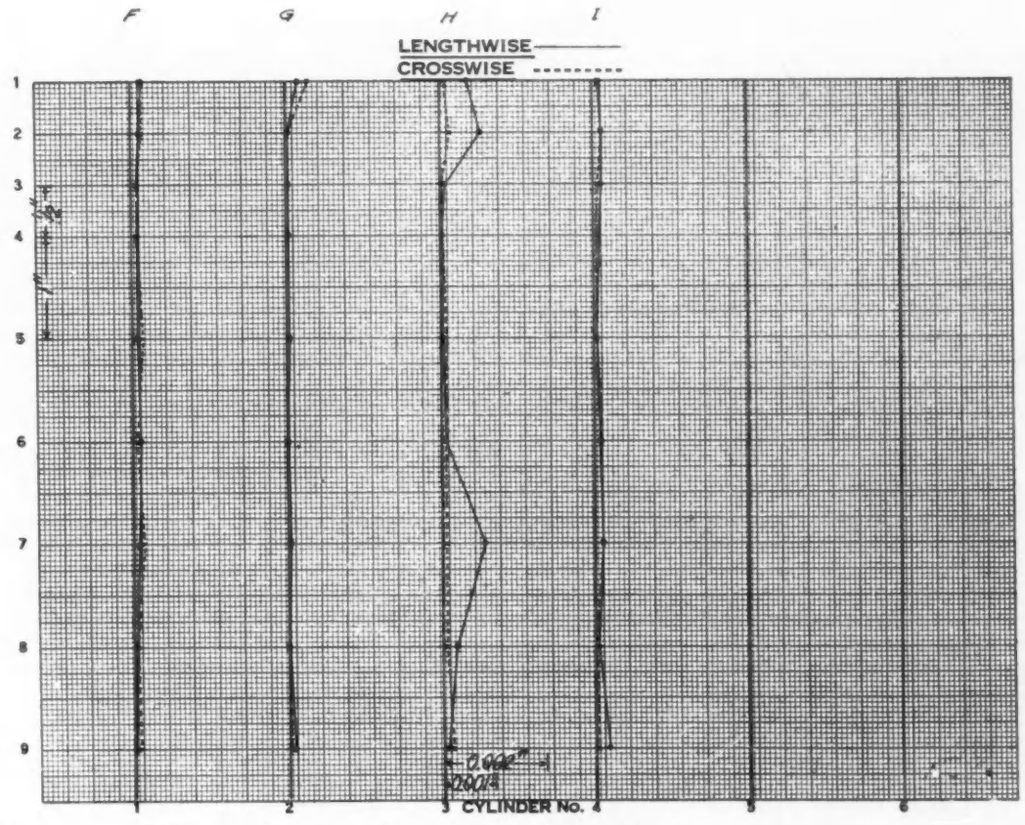
Considerable work has been done in investigating the effect of cylinder-block hardness. It is a well-established fact that soft or porous cylinder-blocks will cause abnormal wear with or without dirt. However, until the iron is made very hard, there is very little difference in the range of wear normally encountered in present-day production practice of 180 to 220 Brinell. It is possible by means of centrifugally cast iron liners with a hardness of around 500 Brinell, to operate under dusty conditions with less bore wear than encountered with the normal cylinder-block iron of about 200 Brinell.

Wider piston-rings with less unit pressure show a lower rate of wear. Piston material and design also contribute, and some of the data submitted indicate that, with abnormal amounts of dust entering the engine, cast-iron pistons show less piston and cylinder-bore wear than do those of aluminum. However, no information is available on the new light-weight cast-steel pistons that are being used by some manufacturers.

All these factors are important, but they merely serve to put off the date of overhaul, and the real solution is to keep the dirt out. The very rapid improvement in air-cleaner efficiency in the last few years leads one to believe that 100 per cent cleaners are within the realm of possibility. I think it can be stated safely that, at the present time, dust and its resulting destruction is no longer a serious problem to the automotive engineer.

Erosion

Assuming that the engine has clean air, then we come to a condition which we have called erosion, or what usually is called scuffing when it is light, and scoring when it is severe. Here the rings or pistons break through the oil film or run where no oil film exists. The result is metal-to-metal contact



of Nine 4000-Mile Tests on the Same Engine with Different Piston-Ring Combinations

which causes wear on both parts. This metal-to-metal contact may be due to any or all of the following conditions:

(1) High-spots on the cylinder wall caused by mechanical and thermal distortion.

(2) High temperature of the cylinder-wall, which burns off the oil film.

(3) Piston-rings that do not give uniform wall pressure or give excessive wall pressure.

(4) High-spots on the piston that create high pressures and dry up sections of the cylinder-wall.

(5) Lubricating oils of low film strength that break down under load.

(6) Oil not present at all, or washed off with gasoline or water, as during cold starting and warming up.

In the prevention of cylinder wear due to erosion the design of the engine, particularly the cylinder-block and piston-ring, becomes of outstanding importance. If these parts could be compounded so that they would run without lubricant, piston-ring scuffing and excessive cylinder wear would be reduced greatly with a consequent improvement in engine life. Piston-ring engineers are making strenuous research efforts toward a solution of their part of the problem, and enough data are available already from the work that has been done to show the great possibilities that are available to us in this direction. Considerable work has been and is being done for the development of better cylinder-block materials. It would be well to mention at this point that, if the engine manufacturers put as much thought and research on cylinder iron as the four or five leading ring companies have done on their alloys, we would have better cylinder-blocks than we have today. Actual tests have shown a 50 per cent improvement in cylinder-bore life, with small additions of copper to the cylinder-block. Nickel, chrome and molybdenum have all contributed some improvement, but very little actual performance data are available as to the actual benefits of each alloy or the amount of each necessary for best results.

The effect of cylinder-block design in preventing thermal distortion is shown by comparing the bore wear on a six-cylinder engine with short water jackets and no water distributor as shown in Fig. 3, with present-day design using header and long water jackets as shown in Fig. 4. Notice the wear at the top ring on all cylinders in Fig. 3 except No. 1 which is well cooled due to its proximity to the water pump. At the bottom of the ring travel the wear is much less, though it is as much as 0.0005 in. The spot where the water jacket joined was at this point and caused considerable trouble with piston seizures. Fig. 4 shows the same size engine with long water jackets and a water distributing tube. The bore wear is practically negligible under identical test conditions.

Numerous tests show that load and speed seem to have very little bearing on bore wear at the brake mean effective pressure encountered in present-day conventional automotive practice *if the engine is cooled properly*. All our tests substantiate this conclusion, and the following data supplied by one member of the committee seem to bear it out. Two eight-cylinder cars were driven, one 15,000 miles and the other 25,000 miles, at full speed with an average maximum bore wear of 0.00064 in. on the first and 0.0011 in. on the second. These figures also show that steady operating conditions give ideal bore wear because owner driving over the same period of mileage would show anywhere from two to five times this amount of wear. If the cylinder-block is of such a composition that it scuffs easily, the bore wear is apt to be excessive because, for low rates of wear, it is absolutely

essential that both the bore and ring face become smooth. Piston-rings can have considerable bearing on bore wear for, if the ring alloy is such that it polishes-in readily under the severe conditions of running in on the new bore, long life will result. If, on the other hand, the ring scuffs, it can spoil the cylinder bore which otherwise would be satisfactory.

The effect of piston-ring design is shown in the following series of tests. Figs. 5 and 6 show the average bore wear for all six cylinders of nine 4000-mile tests on the same engine with different piston-ring combinations. Only three combinations that show any appreciable wear can be noticed. Combination *C*, being by far the worst case, is of special interest because the compression rings are identical with Test *E*. The excessive wear has taken place only in the oil-ring travel and is caused by the high pressure of the oil rings on the cylinder walls breaking through the oil film and at the same time allowing so little oil to go to the top rings that excessive wear occurs there also. Set *H* is of interest as it shows peculiar wear only at the top and bottom of the ring travel. This wear is probably caused by vibration in this ring that occurs when the piston is at the end of the stroke. Fig. 7 illustrates what happens in regard to oil economy, blow-

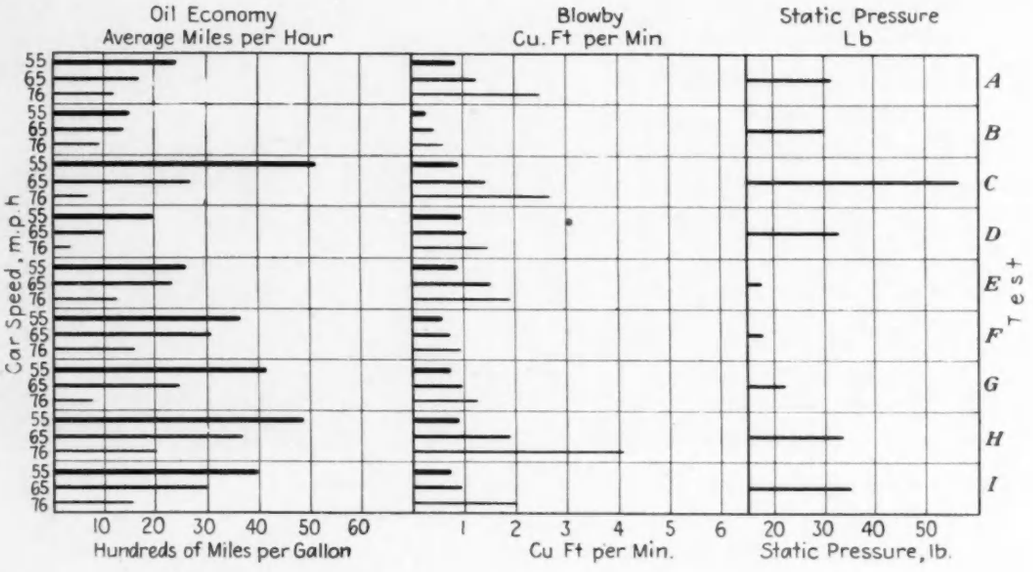


Fig. 7—Oil Economy, Blow-by, and Static Friction for the Nine Tests of Figs. 5 and 6

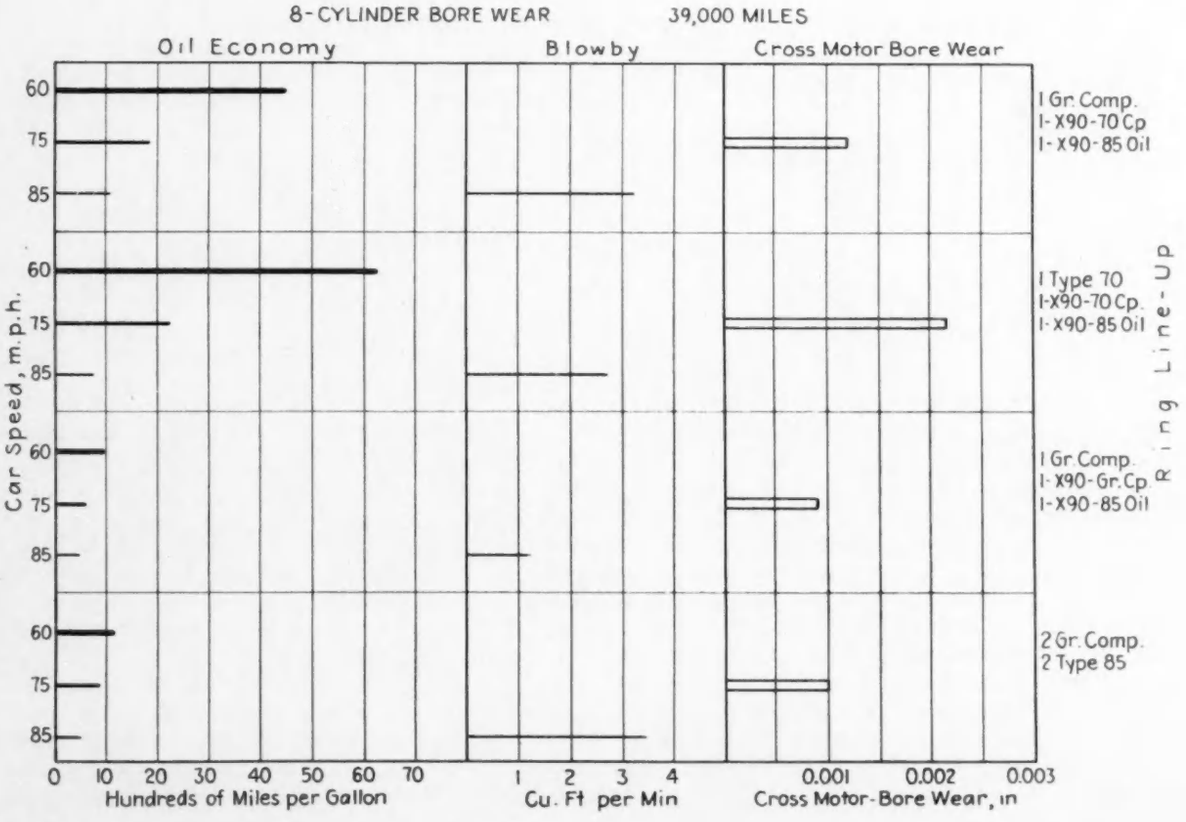


Fig. 8—Oil Economy, Cylinder-Bore Wear, and Blow-by of Four Eight-Cylinder Cars of Same Make Equipped with Four Different Ring Combinations

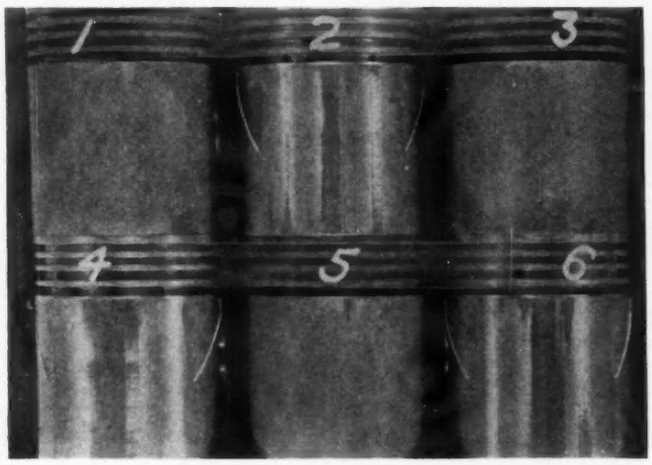


Fig. 9 – Cold Scuffing Test at —10 Deg. Fahr. – Nos. 1, 3, and 5 Anodized; Nos. 2, 4, and 6 Unanodized

by, and static friction. Static friction is measured by slowly applying an increasing load on the top of the piston and ring assembly in the bore until it moves. This friction is reflected in actual operation by loss in gasoline economy. Combination *C*, which had the greatest wear, had by a considerable margin the highest friction. Disregarding wear and friction, this combination would give customer satisfaction as the oil economy is satisfactory. The oil consumption and blowby are shown for the three speeds at which the tests were run. Combination *E* is the production equipment on this engine with two compression and two oil-control rings. All the other combinations were with various spring-ring combinations with springs behind all the oil rings and some of the compression rings. Fig. 8 is the road test on four cars of a well-known eight-cylinder make equipped with four different ring combinations. This test is of value because it shows that, for these conditions, there was little or no relation between oil economy and bore wear. The bore wear with the Type 70 ring in the top groove is probably due to the higher unit pressures of this narrower compression ring. In general, however, good economy and low wear go together, providing that the economy is not obtained by starving the bores or the rings. Generous amounts of oil must be fed to the cylinder bore and piston at all times and controlled by the piston skirt and oil rings in such a manner that the right amount of oil will reach all the piston-rings and still not go in the combustion-chamber.

The worst condition for scuffing piston-rings and bores during normal owner driving is present during the warm-up period after a cold start at low temperature. The piston warms up much faster than the cylinder bore which is surrounded by cold water, with the result that the piston gets larger than the bore. This condition creates tremendous pressure during the time when the lubrication is very apt to be deficient. Fig. 9 shows what happens and how the condition has been improved by means of anodizing. Pistons 2, 4, and 6 are uncoated conventional aluminum pistons, whereas 1, 3, and 5 are pistons of the same alloy and design anodized. Anodizing performs two functions: it makes the surface of the piston very hard and, at the same time, porous enough to hold oil. The uncoated piston actually pulled part of the cast iron right out of the cylinder bore. The rings then scuffed in running over the rough bore, and it takes considerable mileage to smooth everything up again. Tin plating of both iron and aluminum pistons also is effective in eliminating this same condition as the tin acts as a metallic lubricant during the times of high pressures, thus preventing scuffing. See Fig. 10. The large share of the bore wear attributed to corrosion is actually erosion of this type. Fig. 11 shows the effect of adding oil under pressure to the cylinder bore.

Corrosion

To differentiate between corrosion and erosion is one of the most difficult problems of cylinder-wear research because frequently the two go hand-in-hand. The cylinder barrel may rust a little and then be wiped off on the next travel of the ring over the bore, or corrosion from the byproducts of combustion may roughen the surface and the rings rub off the high spots. All the research work expended on this problem to date indicates with a fair degree of consistency that the

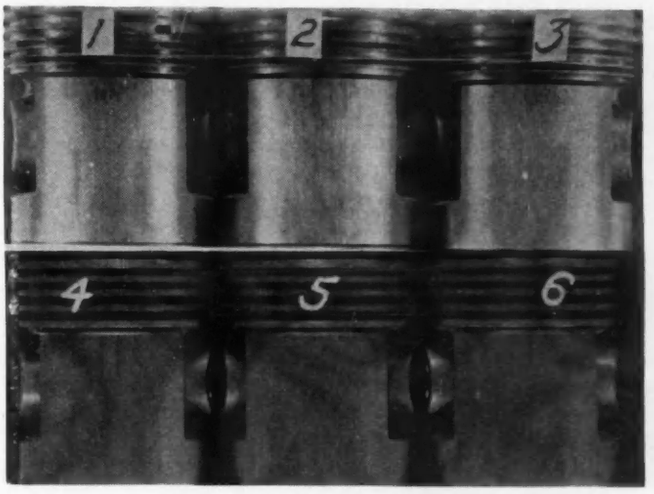


Fig. 10 – Cold Scuffing Test at —10 Deg. Fahr. – Nos. 1, 2 and 3 Unplated Strut Pistons, 5 Cold Starts; Nos. 4, 5 and 6 Tin-Plated Strut Pistons, 15 Cold Starts – Average Clearance 0.0015 In.

worst corrosion occurs while the engine is cold. There is also evidence of some corrosion under high-speed wide-open-throttle operation but the major problem seems to be with cold operation or prolonged light-load, low-speed conditions such as found in bread and milk delivery trucks and other vehicles that operate under very low load factors with frequent changes in temperature and load. When a cold engine starts running, considerable condensation occurs during the first few minutes of operation which impairs the lubrication on the cylinder walls. From the amount of water that goes into the crankcase in the first 5 min. after a start at

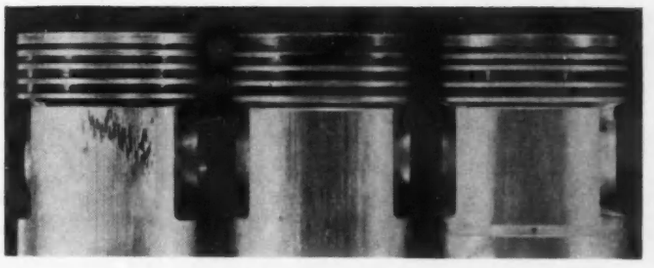


Fig. 11 – Effect of Adding Oil Under Pressure to the Cylinder Bore – (*Left*) Unplated, 12 Cold Starts at 0 Deg. Fahr.; (*center*) Tin Plated, 20 Cold Starts at 0 Deg. Fahr.; (*right*) Tin Plated, Cylinder Lubrication by Pressure, 20 Cold Starts at 0 Deg. Fahr.

—10 deg. fahr., it is apparently raining on the cylinder walls. As there is only a thin film of oil left on the wall from the previous warm running, this film is soon washed away and, as no fresh oil has come up from the crankcase, the rings start running on dry walls, causing scuffing of both rings and walls and leaving bright metal to be attacked by the water and acids.

A number of solutions for this problem are being considered involving both engine design and lubricating-oil characteristics. Here again it is felt that the cylinder-block alloy will play an important part but data as to its absolute influence are very meager.

The use of light oils that get into circulation very rapidly is believed to be one of the best solutions for this condition, coupled with the use of good thermostatic control maintaining fairly high jacket temperatures even under very low-temperature operating conditions. Supplying oil to the cylinder bores under pressure, as is being done by one manufacturer, is to be watched with considerable interest. Real progress in the attack of this problem can be made only with a more careful study of the variables encountered, as the material to date is not sufficiently broad or accurate in its scope to give us a positive solution.

Corrosion can be reduced by the following factors, which give some indication as to the causes:

(1) High jacket temperature and quick warm up.

(2) Generous and positive oil supply at all times.

(3) Proper crankcase ventilation.

(4) Lubrication-oil characteristics.

I regret that the bulk of the data available for a paper of this sort is from test cars operated more or less continuously. Very little information was made available by members of the committee to show the wear under owner-driving conditions. This is an unfortunate condition as, after all, the ultimate measure of the success of any combination is how long it will give satisfaction in the average user's hands. We have the satisfaction of knowing that a great many of the changes that have shown an improvement on test cars also have shown improvement in the owner's hands.

The things that we do not know are, first, how good should oil economy be to give long life under average driving conditions and, second, what lubrication-oil characteristics are desirable for all-around operating conditions? In other words, will compounded oils actually improve the life of the engine in the hands of the average owner? Here is a field for very valuable research in the laboratories of the oil company.

In closing I would like to suggest that a committee be formed under the auspices of the S.A.E. embracing a group of engineers that are in a position to collect bore-wear data under all conditions of operation. I feel that considerable progress could be made by the industry as a whole in a co-operative study of this sort.

Discussion of Roensch Paper

Discusses Effects of Bore Finish and "Combination" Rings

– Paul S. Lane

Metallurgical Research Engineer, Koppers Co.

IT is interesting to note that Mr. Roensch, in his analysis of the three main causes of cylinder wear, lists "abrasion" and "erosion" as being generally more responsible than corrosion. I think too that this is the proper relationship, in spite of the fact that recent British investigators appear to feel that nearly all cylinder wear is corrosion, involving chemical attack in some form or another.

Considering abrasion – most all will agree to the importance of bore finish, and there is little doubt but that it is an important factor in determining subsequent ring and cylinder life. In the case of a new engine, or one with newly finished bores, it is our opinion that practically all of the wear occurring, say in the first several thousand miles, takes place during the first few hours of operation, rather than progressing at a rather uniform rate from start to finish of the run. I would be interested to hear Mr. Roensch's comments regarding this.

We recently completed some laboratory wear tests, using a machine of the "brake-shoe type," wherein the revolving drums representing the cylinders, were finish-ground circumferentially and transversely. These tests, although not duplicating engine conditions, indicated the following after one hour's run:

(1) Cylinder wear was doubled with transverse grinding, using rings of the same or higher hardness than the cylinder.

(2) Piston-ring wear was increased more than 12 per cent with transverse grinding, ring hardness being the same or greater than cylinder hardness.

(3) Using soft rings of 200 Brinell or less, transverse grinding seemed to load, similar to a file on a soft material, and this condition gave less apparent cylinder wear but the rings wore away very rapidly.

One would certainly feel, therefore, that cylinders should be finished codirectionally with ring travel, and in some cases this method is now being attempted.

Regarding erosion – Mr. Roensch has given us quite a complete picture, and this is one thing that we all should know more about. When metal-to-metal contact does exist, indicating a "dry period" for one reason or another, scuffing or "galling" occurs, and may be entirely erased, only to form again later on during another dry period. This tendency to seize or scuff, although related to surface finish, is more likely a function of the metal structure. Elimination of this trouble, considering only the piston-rings, calls for a ring material that will give maximum life with suitable physical properties under lubricated conditions, but which also will be relatively "non-seizing" or "self-lubricating" during the dry period. This latter quality is present to only a limited degree in present-day conventional piston-rings, and the search for such an all-encompassing alloy or material is still going on.

Even though the main functions of the piston-ring are to seal and hold compression and to control oil, we must not lose sight of the fact that rings are fundamentally also "bearings." As such, it would seem logical to incorporate in the ring a bearing-metal structure, in so far as other necessary physical properties will allow. It must in all truth be stated that, due to the very light sections of present-day rings, such efforts are hampered seriously.

A rather new and successful attempt to strike a compromise in our desires to satisfy all of the foregoing requirements has been found in the use of iron-bronze "combination" rings. These rings have been applied over rather a wide field with good success, particularly in steam and Diesel work where ring sections are somewhat heavier than in the automotive engines. In fact, rather startling increases in ring and cylinder life have been obtained where the groove depth and face thickness allow two complete rings, one of bronze and the other of cast iron, operating in the same piston groove. The ring unit is so constructed that, although the bronze is free to "glaze" or "slick", the cylinder surface with a copper-rich and, hence, non-seizing film, its further rapid wear is retarded by the cast-iron portion of the ring with which it is interlocked loosely.

Rings of the "Gold-Seal" type, having a strip of phosphor bronze rolled into a groove machined on the outside diameter, are probably familiar to a great many present, and these rings carry out the same thought in lighter section rings. They are being more and more widely used, and are not to be considered as belonging to the "freak" or "trick" family, since they have proved themselves of much benefit when properly applied. They are being used in truck, Diesel, air, and refrigeration machinery.

The iron-bronze combination ring and the Gold-Seal ring, although they may not eliminate the source of the trouble, offer so much improvement in ring and cylinder performance, particularly as regards scuffing, that their further use and investigation seems warranted. In

both of these types we at least approach, through the use of two dissimilar metals, the ideal material mentioned before, namely, suitable physical properties for sealing compression and so on, and for operation under oil film conditions, and also a bearing-metal effect in that they are much less prone to seizure or scuffing, but have, to a more or less degree, self-lubricating properties during the dry periods.

In closing, I would like to mention another interesting, and also we might add, discouraging feature regarding bearing qualities of cast iron. Some preliminary tests have indicated that the better wearing irons or structures (incidentally those having a distinctly heterogeneous structure similar to a bearing metal), seem more prone to scuffing, so we must be careful that, in our quest for the "slowest" wearing material, we do not add to scuffing and seizure tendencies. This observation, although as yet not established definitely, should at least furnish sufficient "headaches" for some of us during this new year.

City Fleet Experience Reported

– C. B. Lindsey

Superintendent of Automotive Equipment, Los Angeles Railway Corp.

TO the Los Angeles Railway Corp., operating a fleet consisting of 233 coaches, 45 automobiles, and 59 trucks and tractors, the subject of cylinder-bore wear is one of considerable importance.

The major bulk of the equipment being operated within the metropolitan area and on paved streets, premature wear caused by excessive quantities of dust mixed with the air intake has not been experienced.

During the warm weather coaches operated continuously are apt to run low on water and, unless the operator is on the alert, damage from this source, due to distortion, ring scuffing, and so on, will be considerable.

Incidents of this nature are reported to the Transportation Department if negligence is apparent so that the driver may be disciplined accordingly.

The first indication of wear in an engine usually is reported by our fuel clerk who notices a drop in the miles-per-gallon of fuel and miles-per-quart of oil and if, after the usual tests for leaking valves, and so on, it appears necessary to take the engine down, the cylinders are calipered and, provided the wear does not exceed 0.010 to 0.012 in., new piston-rings are installed on engines of 30- to 40-passenger coaches.

In the older types of engines, this installation usually is necessary around 50,000 miles. After a total of from 0.015 to 0.020 in. has been reached, cylinders are reground and new pistons and rings fitted. This operation usually can be performed three times before it is necessary to discard the engine block, provided of course the walls have not been scored heavily or otherwise damaged. When this damage occurs and the cost of a new block is considerably in excess of a repair job, we have had sleeves installed with good results.

In the modern engines with which the newer types of coaches are equipped, a very different picture is presented. Cylinders of engines inspected, which have averaged from 200 to 300 miles per day over a period of one year, show little or no appreciable wear. One engine inspected recently after running 161,249 miles averaged 0.0015 in. wear per cylinder at the end of the ring travel.

A fleet of 20 coaches equipped with the aforementioned engines has run an aggregate total of 2,500,000 miles without regrinding, although piston-rings were replaced at approximately 57,000 miles on account of increased oil consumption.

The remarkable mileage obtained from the cylinders on these engines is undoubtedly due to the hardened sleeves with which they are equipped, and these sleeves can be replaced, according to the manufacturer, after several re-grinds, provided the cylinder-block has not disintegrated from old age in the meantime.

Copper-wool oil-saturated air cleaners are used on most of our later model engines; they also are equipped with various types of oil filters. Lubrication is watched very closely, and the crankcases are refilled when necessary. An S.A.E. 60 Pennsylvania oil has been found most suitable for service and economy. This oil is changed, as directed according to analytical report, and averages approximately 6000 miles per change.

One of the most prolific sources of premature cylinder wear is caused by fitting the pistons and rings too tightly when engines are rebuilt.

Mechanics, endeavoring to turn out a first-class 100 per cent job, leave minimum clearances, under the impression that higher compression and greater oil economy will be obtained. Unfortunately this impression is not so as, even though an engine will perform nicely on the running-in stand, in actual service distortion occurs which invariably results in scuffing or actual scoring and seizure, which results in an equipment failure and an expensive repair job.

All of our coaches are started and warmed up by mechanics, and these men have been properly instructed in this procedure as excessive wear and damage will result if the engine is over-speeded when cold. Although this practice is somewhat expensive, we consider that it pays big dividends, as many inexperienced operators will "race" the engine and run long distances in low gear if short of time, endeavoring to hurry up the warming-up process and arrive at their destination on time.

Compares Effects of Green and Seasoned Bores

– J. H. Ballard

Chief Engineer, Sealed Power Corp.

IN commenting on Mr. Roensch's paper, in the main I am in accord with the statements and conclusions that he has reached. As pointed out by the author, the problem of cylinder-bore and piston-ring wear is a complicated one, principally because of the many factors involved. Unfortunately no satisfactory solution can be arrived at by investigating independently any one of the principal contributing factors, namely, abrasion, erosion, and corrosion.

The area of the piston-ring is, of course, very small compared with the total cylinder area over which it sweeps; therefore, rings generally suffer most from abnormal operating conditions and, as a result, are apt to be criticized for results which they have not caused.

There is no doubt in my mind but that the designing engineer has corrected to a great extent the evils of thermal and mechanical distortion, localized hot-spots, improper piston design, and so on, and these efforts, I believe, have been one of the outstanding factors in bringing today's motor to its present state of efficiency. In addition, the lubrication engineer and the air-cleaner engineer have made remarkable progress in their particular phases of the problem.

The high unit pressures in piston-rings, which are necessary to meet the present-day requirements, have created a problem in oil-film strength which the lubrication engineers have had to face, and I believe it would be impossible to operate successfully the present-day motors as far as the pistons, piston-rings, and cylinders are concerned if the oil engineers had not done their part.

I believe that the piston-ring manufacturers have exerted themselves to the utmost to keep their design and product up to the standard necessary for operation in the present-day motor.

There are other factors that enter into the problem of cylinder and piston-ring wear which may or may not come within the province of any group of engineers mentioned previously. Among these factors are the care used in production, assembly, and breaking-in of the motor before it is delivered to the customer, and the care that the owner gives the motor after it becomes his property.

It would seem that with the careful design and manufacture of the present automobile engine, they should give fairly consistent performance; yet, I believe we will all agree that there is considerable variation in the performance of motors of the same make, especially from the standpoint of oil control. This variation, I am inclined to believe, is often traceable to the way in which the motors are started off in service. It is during this critical breaking-in period that much damage can be done to cylinders, pistons, and rings.

I would like to illustrate my point. First, let us consider an engine which it was recently my pleasure to observe. It had operated 62,000 miles on a road test, 30,000 miles at 70-80 m.p.h. and 32,000 miles at various speeds. The average speed for the 62,000 miles was a little more than 60 m.p.h. with an average oil consumption of 2000 miles per gal. for the 62,000 miles. The maximum wear on the cylinders at the top of the ring travel was 0.0026 in., and at the bottom of the ring travel it was 0.0005 in. The top piston ring had worn 0.005 in. on the radial thickness, and the oil rings 0.006 in. on the radial thickness.

On the other hand, I know it would be entirely possible to take a similar engine and, by subjecting it to improper breaking-in, have as much piston-ring wear result in one hour of high-speed, full-load operation as was found on the engine just mentioned after all tests were completed.

Another factor that has come to our attention is a condition found in cylinder bores wherein, for some reason or other, due to surface characteristics, we have found a problem of ring scuffing. Up to the present time we have not been able to tie up this surface characteristic with what is commonly known as roughness or smoothness, and it seems to me that there is a certain process of seasoning that takes place in the bore during the initial operation which tends to eliminate to a great extent one cause of ring scuffing. Many times we have had the initial piston-rings scuffed in a test engine and, when a second set of rings was installed, no ring scuffing was apparent. Sometimes, however,

a third set of rings is necessary before this scuffing is eliminated entirely.

Recently, we conducted a test to determine the amount of running necessary to season the bores to a point of elimination of ring scuffing. In order to do it we selected a well-known engine, 1937 model, and honed the bores with a 500 grit stone to what would be considered a good commercial finish. We cleaned them up properly and installed a set of conventional rings. This engine was brought up to running temperatures and run for 1 hr. at 3850 r.p.m., full load. Severe scuffing was apparent on both compression and oil rings. New rings were installed without touching the bores, and the test duplicated. This procedure was repeated, and not until the seventh run were the rings found to be free from scuffing, although they had been subjected to the same test as had the first set.

Another experience that I would like to mention was with a six-cylinder heavy-duty truck engine on which we conducted some oil-consumption tests. Before this engine was sent to our laboratory, it had been run on the test stand and the No. 5 piston had scored. This piston was removed, the barrel re-honed, and a new piston installed. However, the cylinder was honed by hand, and a rather rough job was done. The spiral marks from the rough hone were very pronounced, and this bore did not compare in smoothness with the other five.

After our preliminary test, which was run at practically full load and maximum speed, the rings that had been in the five untouched cylinders were scuffed, while strangely enough the rings in the re-honed bore, which was considered very rough, came through in perfect shape.

I realize, of course, that one test such as this is far from conclusive, but the experience does serve to bring out the fact that many contradictory results are observed when considering this whole problem.

All this experience leads me to believe that there is a difference between what could be called a "green" and a "seasoned" bore finish. Further work should be done on this subject.

I believe with Mr. Roensch that a committee should be appointed to study this problem, bearing in mind that the metallurgical engineer and the production engineer should be represented in such a committee.

The Set-Up for Trans-Pacific Operation

THE sum total of trans-oceanic transport experience in the log books of the world's airlines is still quite small compared to the astronomical figures that represent land-transport flying; yet the ratio is an increasing one. Just recently Pan-American Airways System completed a half million miles of Pacific flying and, of course, its entire Pacific operation is backed by almost a decade of extensive over-water operations in the Caribbean and along the North and East coasts of South America.

The German Luft Hansa and Air France are in regular operations across the South Atlantic; England with her new Empire boats is preparing for extensive over-water operations on its long route from England to Australia, and heavier-than-air service across the North Atlantic seems to be in immediate prospect.

The object of this paper is to present a summary of the problems connected with such flying, as we have encountered them in the Pacific Division of the Pan-American Airways System. It will take the form of a running description with comments of a typical flight along the airway from Alameda, Calif., to Manila, P. I.

As you know, the particular route under discussion is some 8200 miles in length. It will be almost 9000 miles when it is extended to the coast of Asia. It is plenty of miles by anyone's yardstick; for example, it is more than three times the width of our continent between New York and San Francisco.

In our operation, these 9000 miles are broken into stages – on a westward flight at Honolulu, at Midway Island, Wake Island, Guam, and Manila. The longest stage is, of course, the 2430 miles from the mainland to Hawaii, which, incidentally, is 400 miles longer than any stage of the North Atlantic by way of either the Bermuda-Azores route or the Newfoundland-Ireland route. Beyond, the longest stage, that between Guam and Manila, is only 1589 miles.

Each island stepping stone is equipped with an ocean air base. These bases naturally vary considerably to fit local conditions but, from an operating point of view, consist of complete terminal facilities. At Midway and Wake Islands we have established a complete radio communication center, operating on various frequencies with a long-range direction finder; complete weather equipment for surface and upper-air sounding; facilities for all of our personnel; complete fueling facilities that enable us to fuel our flying boats at the rate of approximately 100 gal. per min.; storage facilities for a large quantity of fuel; complete lighting equipment for the cantonment consisting of Diesel-electric units; modern hotel facilities for the convenience of our passengers; waterfront facilities consisting of docks, floats, and motor boats. The general development of these facilities is the result of our operations in the Caribbean and along the East coast of South America. At each station are permanent crews consisting of the airport manager, who is the senior company representative; chief mechanic and additional mechanics for servicing and maintenance; chief radio operator and two additional operators; coxswain and seamen for the handling of motor boats and waterfront facilities; commissary steward, cooks, bakers, and servants for the maintaining of our modern, up-to-date hotel facilities.

The key men have been trained in other divisions and are now on a more or less permanent status, operating on duty between the island terminals and the more populated centers such as San Francisco, Honolulu, and Manila.

In addition to this base, which might be called a standard base, there are special facilities at Manila for doing maintenance and inspection work required before the long return to California and, at Alameda on the eastern shore of San Francisco Bay, are maintained elaborate shops where each plane is taken for complete maintenance, inspection, and service before the next westward flight. After the flying boat is hauled out of the water, it is moved immediately to the hangars. There very thorough inspection is made of the entire ship, instruments removed, engines thoroughly gone over, complete interior removed, sound proofing removed in instances where necessary, and inspection carried on in such a manner that service personnel immediately can prepare the ship for the next flight. Engine changes are made in pairs after three round trips to Manila. This complete inspection and service is under the jurisdiction of the division engineer and is set up as standard Pan-American Airways procedure, except the inspection and service of the radio equipment which is under the supervision of the division communications engineer.

Excerpt from the paper, "Operating Problems of Flying Boats," by C. H. Schildhauer, presented at the National Aircraft Production Meeting of the Society, Los Angeles, Calif., Oct. 15, 1936.

Aircraft Spotwelding Efforts Benefit Many Industries

By Bruce Burns
Consulting Engineer

YIELDING to recent intensive efforts of aircraft and equipment engineers, spotwelding – an old process – is being developed and refined to embrace new materials, higher speeds, stronger welds.

Results of these efforts will benefit not only aircraft manufacturers themselves, but will reach out into many industries entirely outside of the automotive field.

Four years ago spotwelding in aircraft construction was limited to one or two thicknesses of one or two materials. Today a modern landplane may have 15,000 to 20,000 welds in a dozen different thicknesses of twenty or more materials; a seaplane with spotwelded floats may have even more. Welding currents of 1000 to 50,000 amp. may be required, with welding pressures of 50 to 1500 lb. per sq. in. and accurately controlled periods of current duration from 0.01 to 0.10 sec. Welding set-ups may have to be changed several times per day, or even per hour. Unusual range and extreme flexibility are required to meet such production requirements.

This paper briefly outlines the fundamentals of spotwelding of aluminum alloys and corrosion-resistant steels, presents various examples of production-welded assemblies, discusses welding equipment, and touches upon production tooling.

DURING the last four years, spotwelding has come into general use in the aircraft industry. The reasons for its adoption are four-fold:

(1) Cost. On certain classes of work where advantage may be taken of the characteristics of the method, spotwelding offers substantial economy over any other method of joining together two sheets of metal.

(2) Appearance. In certain applications, notably in the interior fittings of passenger-carrying airplanes, the smooth surface on the face of panels or assemblies fabricated by spotwelding is of definite aesthetic value.

(3) Aerodynamics. By elimination of projecting rivet heads on external surfaces of the ship, drag may be reduced and boundary-layer conditions improved. Spotwelding may be prescribed for such applications only after careful analysis of stress conditions and of the stress-resisting characteristics of the spotweld.

(4) Necessity. In the case of certain materials, such as the corrosion-resistant steels, spotwelding is usually the most economical method of joining and, in the lighter gages of these materials, it is the only practical method, regardless of cost.

[This paper was presented at the National Aircraft Production Meeting of the Society, Los Angeles, Calif., Oct. 15, 1936.]

History

Spotwelding itself is an old process; it is probably impossible to determine when the first attempts were made to apply it to construction of aircraft. It is certain, however, that sporadic attempts were made some 7 or 8 years ago to use the method for joining parts made of steel and that, at least 4½ years ago, one manufacturer seriously undertook the study of the problems involved in welding the strong aluminum alloys. Since that time substantial progress has been made both in the welding of the steels and of most grades of aluminum alloy; at the present time almost all major aircraft manufacturers have spotwelding equipment actually in production or preparing to go in production.

The difficulties that stood in the way of practical production spotwelding as little as 4 years ago were manifold. No manufacturer knew what was required either by way of equipment or welding technique. As the manufacturers of welding equipment and the suppliers of the materials to be welded apparently could not supply this information, the manufacturer started with whatever equipment seemed to be most suitable, often building a considerable part of it, and endeavored to work out for himself the essentials of welding technique.

Although deadly serious at the time to those who were endeavoring to solve the problem and to those who were footing the bills, the situation in retrospect has its amusing aspects. The welding machine usually lacked sufficient electrical capacity, the timer usually was incapable of delivering electrical energy in accurately controlled periods of sufficiently short duration, and the materials to be welded seemed to be just plain stubborn. The technique that produced satisfactory aluminum coffee pots merely ruined aircraft materials; the supplier of both continued to use his own excellent equipment to show how easy it was to weld the easily welded

materials, and left the difficult problem of welding the strong alloys to the man who had to use them – and pay for them.

The work being done in each plant often was conducted with such secrecy that the machine operators themselves did not know what they were doing, and the bamboo telegraph buzzed with erroneous and misleading information. One manufacturer would be making discouragingly slow progress with equipment that cost him several thousand dollars, only to hear that so and so was about to go into production with a machine assembled from pieces of a Model T Ford and an Ingersoll watch. He would be at the point of eternally damning all spotwelding when a break of luck and momentarily consistent performance of his equipment would reward him with a small assembly that not only looked beautiful, but also stayed together when picked up by one corner. If, at the same time, he learned that competitor so and so was not using an old Ford magneto, but was actually depending entirely on bear oil and sorcery, our manufacturer promptly uncrated the last shipment of strong aluminum alloys, wiped from the sheets the now-dried crocodile tears with which they had been packed, and attacked his problem with renewed vigor. The graph of progress and enthusiasm for this period would make Manhattan's skyline seem like the horizon of the great plains.

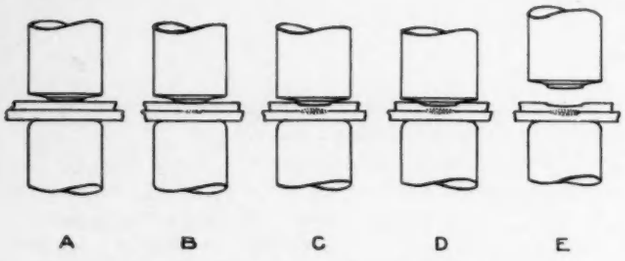


Fig. 1 – Steps in Making a Spotweld

The situation has cleared up remarkably in the last two years. Progressive manufacturers of equipment have produced welders and timers designed expressly for aircraft requirements; the Materiel Division of the Army Air Corps and others have conducted exhaustive experiments on welding technique and have disseminated the information gained; and there has been considerable interchange of information among the various manufacturers. It is now possible for a manufacturer to install excellent equipment and to bring his technique to production standards at a fraction of the cost borne by the pioneers.

The Process

At the risk of covering ground that is familiar to all of his readers, the author will review briefly the essential elements of spotwelding in order that its present application may be understood clearly. Spotwelding consists of placing two or more pieces of metal to be joined between a pair of electrodes, applying pressure to the electrodes to force them against the work, thus forcing the pieces of work together and, with continued pressure, supplying a large amount of current for a short period of time.

Fig. 1 shows the steps in making a spotweld. In position *A* the electrodes are brought into contact with the work and the two pieces are pressed together. At *B* the current has started to flow, and the surfaces of the work in contact are being heated by the passage of this current. Due to the impossibility of direct observation we do not know exactly what takes place at this time. The generally accepted theory is that, because the surfaces of the sheet are in intimate contact only where the high-spots are pressed together, these high-spots first soften or melt under the heating effect of the current and, as they give way under pressure, other portions of the sheet surfaces come into contact and carry their share of the current. The spot thus begins at one or more points in the plane common to the two sheets and extends in all directions from these points.

Continued application of current and pressure increases the diameter and thickness of the heated zone and the penetration of the electrodes into the work, as shown in positions *C* and *D*. Since the heat generated in the weld zone is being dissipated continuously into the sheet and the adjacent electrodes, the melting or softening of the material in the weld ceases as soon as the current is shut off. By accurate control of the welding conditions, it is possible to keep the size and shape of successive spots within reasonably close limits.

Fig. 2 presents diagrammatically another form of spotwelding known as roll welding. In this case rotatable rolls are used as electrodes, and the materials to be welded are fed between them under pressure while the current is applied intermittently. If the work speed be high in relation to the number of current impulses in a given period of time, a series of spotwelds may be produced at accurately spaced intervals. If the work speed be low and the frequency of current impulses high, these welds will overlap to form a continuous seam.

Figs. 3, 4, and 5 are macro-photographs of sections through spotwelds which have been polished and etched.

Although spotwelding can be done with direct current, and is so done in Europe, the widespread use of alternating current in this country years ago led the way to development of alternating-current equipment. Practically all commercial spotwelding in the United States is done with alternating current, which has the advantage that it can be interrupted at or near the zero point of the wave by some synchronous device operating at high voltage and low current values, the electrical energy then being converted by means of transformers into high amperages at low voltage values.

Fig. 6 presents diagrammatically a general-purpose welder for aircraft work. Such a machine should be able to handle from 0.003-in. stainless-steel alloys to 0.093-in. 24ST strong aluminum alloy. Current outputs should be as indicated in the left side of the diagram and, between these limits, it should be possible to change current values in increments or decrements of not over 7 per cent. In the particular set-up

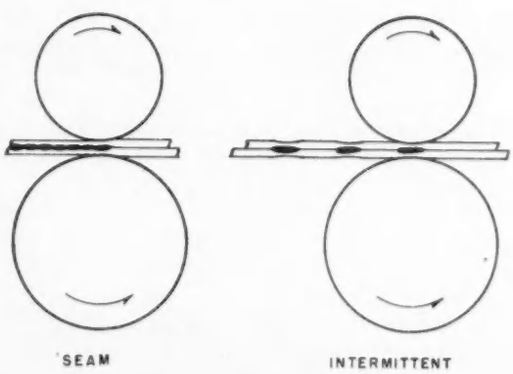
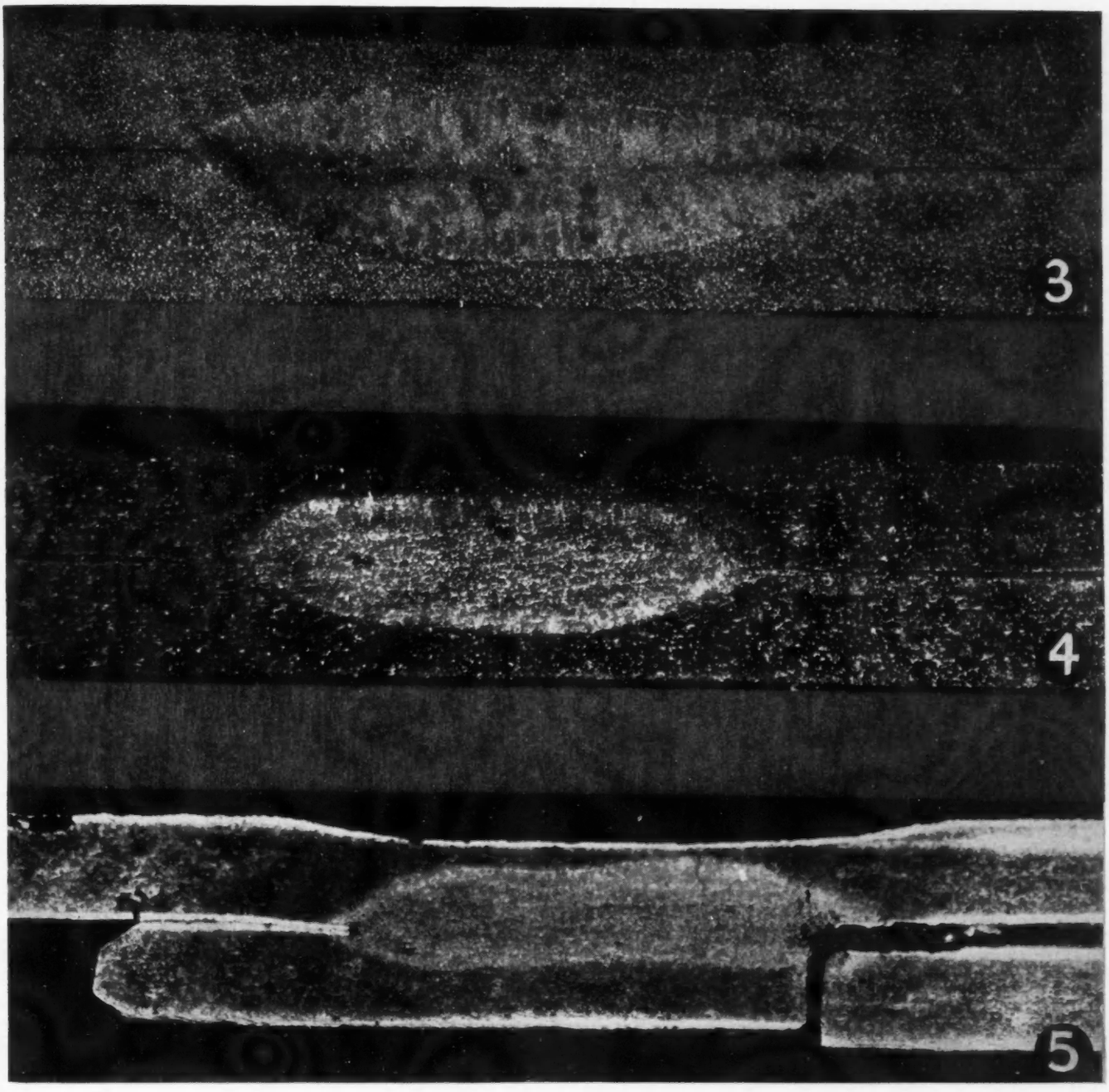


Fig. 2 – Roll Welding



Figs. 3, 4, and 5 – Macro-Photographs of Spotweld Sections That Have Been Polished and Etched

Fig. 3 – 0.051-In. Aluminum Alloy 3S½H

This is a typically clean spot, as obtained with easily welded material. The zone of material that has been molten or re-crystallized by heat and pressure is clearly distinguishable from the parent metal

Fig. 4 – 0.025-In. Strong Aluminum Alloy 24ST, Bare

Close examination of the weld structure will reveal a few minute blowholes near the central plane of the spot; these blowholes are more or less characteristic of welds in this material. They would have no measurable effect upon static strength; their effect under fatigue stress conditions may be minimized by making the weld diameter large in proportion to sheet thickness.

Fig. 5 – Section, Fatigue Failure – 0.025-In. Strong Aluminum Alloy 24SRT, Coated (Alclad)

A typical fatigue failure. Space does not permit discussion of this phase of the work; but this photograph is included because it shows at the left-hand edge of the spot a small section of aluminum skin which apparently lies within the weld zone. Doubtless this section was as hot as the adjacent 24S material but, due to the higher critical temperature of the pure material, the deformation that caused re-crystallization in the alloy base had no effect upon the aluminum skin.

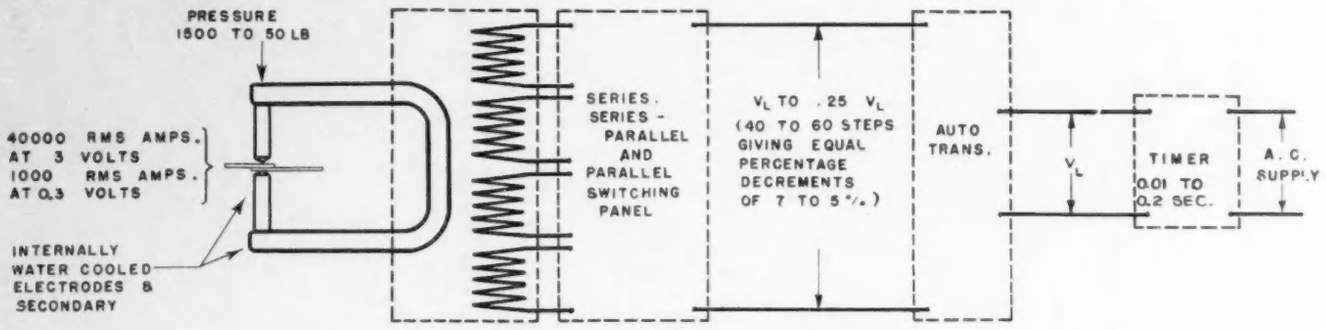


Fig. 6 – Diagrammatic Sketch of General-Purpose Welder for Aircraft Work

shown, this range is obtained by the combination of an auto transformer and series-parallel or parallel connection of the welding-transformer primary coils. The timer should be capable of supplying current in accurately predetermined intervals ranging from 0.01 to 0.20 sec. in as small steps as 0.020 sec. or less. Electronic controllers are now available to cover this range in steps of one-half cycle which, with 60-cycle current, makes each step 0.008 sec.

Fig. 7 shows the generalized relation between the various controllable factors in welding and indicates the rather narrow range in which consistent production welding may be carried out. This chart was worked out three years ago for the then commonly used aluminum alloy 17ST, and the quantitative values on the scales can be applied only to this material. This material has been superseded largely by other aluminum alloys, but similar charts for the newer materials indicate that the general characteristics of the curves are similar, although the quantitative values may vary over a wide range.

In the upper-left quadrant of this chart (Fig. 7), spot

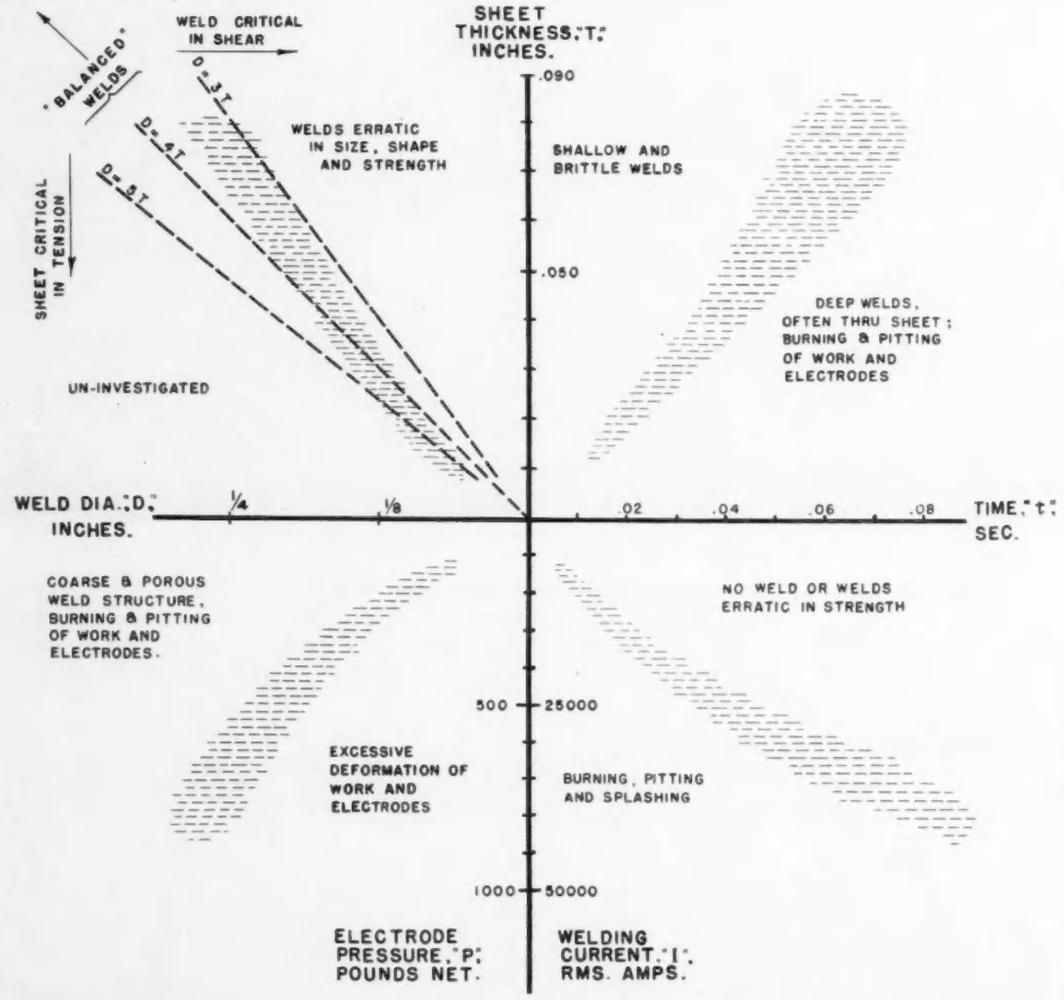


Fig. 7 – Interrelation of Welding Conditions – Aluminum Alloy 17ST (Copper, 4 Per Cent; Magnesium, 0.5 Per Cent; Manganese, 0.5 Per Cent)

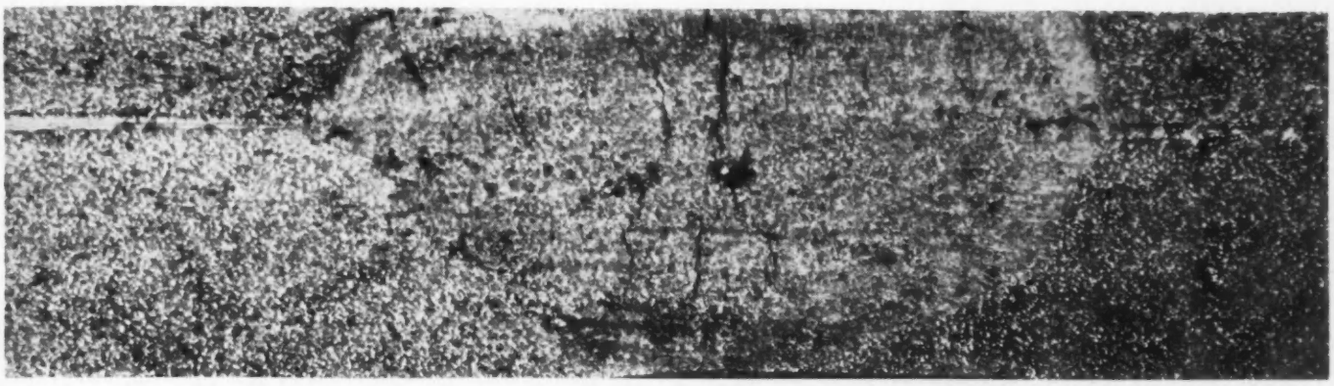


Fig. 8 – 0.025-In. Strong Aluminum Alloy "Alclad" and 0.051-In. Strong Aluminum Alloy 17ST Bare

This "spotweld" points out the consequences of endeavoring to spotweld these materials outside the proper range of conditions. Here the current intensity was too great, the time of current application too long, and the electrode that was pressed against the thinner sheet has been permitted to form a copper-aluminum alloy surface of high electrical resistance on its face. The thinner sheet has been burned to a crisp, and the whole weld structure is shot through with cracks.

diameter is plotted against sheet thickness; the shaded zone represents the ratios that are commonly obtained in production practice. It will be noted that the shaded area goes from a 5:1 ratio in the thinner gages to a 3:1 ratio in the heavier gages. This shift from the optimum 4:1 ratio line is a matter of production economics. In the thin gages it seems impractical from the production standpoint to keep the diameter of contact of the electrodes much smaller than 0.06 in. and, in the heavier gages, the pressures and currents necessary to maintain the 4:1 ratio become excessive.

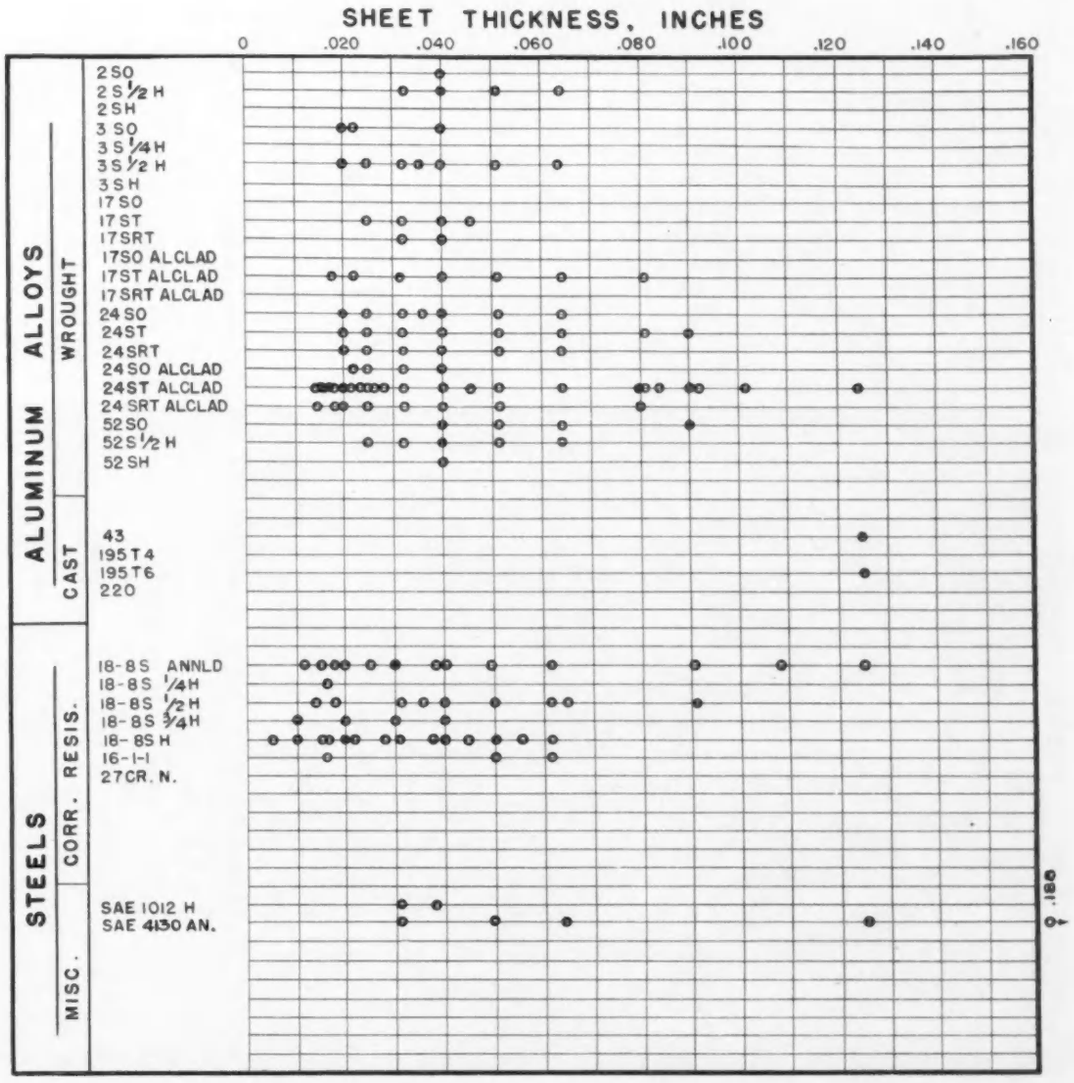
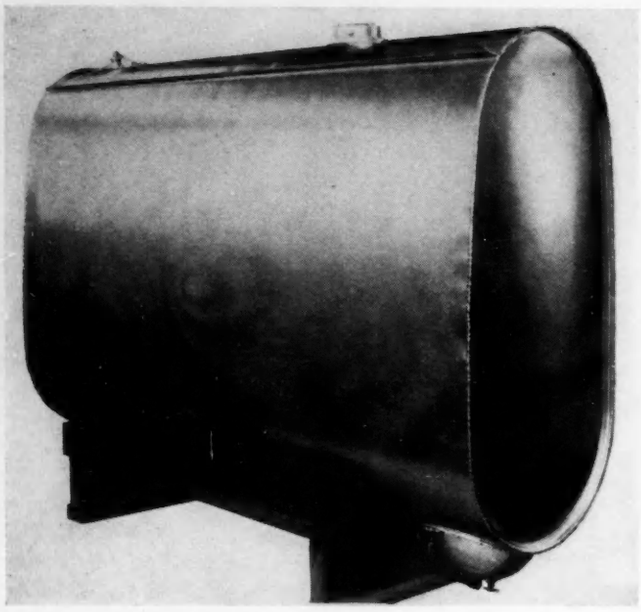


Fig. 9 – Materials Spotwelded in Production (Combinations of Thicknesses and Material Not Shown)



Courtesy Glenn L. Martin Co.

Fig. 10 – Fuel Tank, 250 Gal., 45 In. High, 21 In. Wide, 60 In. Long, 0.051-In. and 0.064-In. Aluminum Alloy 52SO

Approximately 4500 single spotwelds. Longitudinal seam roll-welded with approximately 800 spots; end bulkheads and fittings torch-welded. Pressure test, 3½ lb. per sq. in.

Starting from the indicated spot diameter for a given gage of material one may project a line vertically downward to determine in the lower-left quadrant the optimum pressure and, from this point, a horizontal line carried into the lower-right quadrant will indicate the necessary current. Similarly a horizontal line drawn from sheet thickness into the upper-right quadrant shows the desirable time of current application. (With the data plotted in the particular form here used, one cannot project vertically from the time quadrant to the current quadrant.)

Certain of the aluminum alloys are considerably less critical than 17ST and permit greater variation in the welding conditions particularly with regard to timing. Others of the aluminum alloys are even more critical than the material here represented and require extremely accurate control of all variables. In the case of the corrosion-resistant steels it was indicated for a time that very short and accurately controlled periods of current application were desirable to minimize carbide precipitation. Subsequent investigations have indicated, however, that carbide precipitation is negligible in 0.025 in. thickness of material with time intervals of the order of 0.133 sec., recent improvements in these alloys tending to stabilize the carbon constituent, probably rendering them substantially free from carbide precipitation with any timings that are practical for use in production work. To minimize electrode maintenance, present practice seems to be to use the shortest convenient timing that will give satisfactory mechanical weld characteristics.

The author would be the last person to contend that it is impossible to weld aluminum alloy 17ST with conditions other than those indicated on this chart; as a matter of fact, he feels that present and future research may produce substantially different technique. In the meantime the approximate zones here indicated show one region in which consistent results may be achieved. With the thought of keeping production flowing smoothly through the inspectors' hands and with no intent to discourage the inquiring experimenter, the author calls attention to the notes lying between the shaded areas and the coordinate axes of Fig. 7. Fig. 8 graphically depicts a disastrous pitfall.

Scope of Materials

Fig. 9 is a chart showing various materials commonly used in aircraft construction. Opposite each material a circle indicates the thicknesses of that material which, at the present time, are being spotwelded in actual production work. This chart is compiled from data submitted by a number of the major manufacturers, but it does not pretend to be complete. It gives an astonishing picture of the variety of work handled.

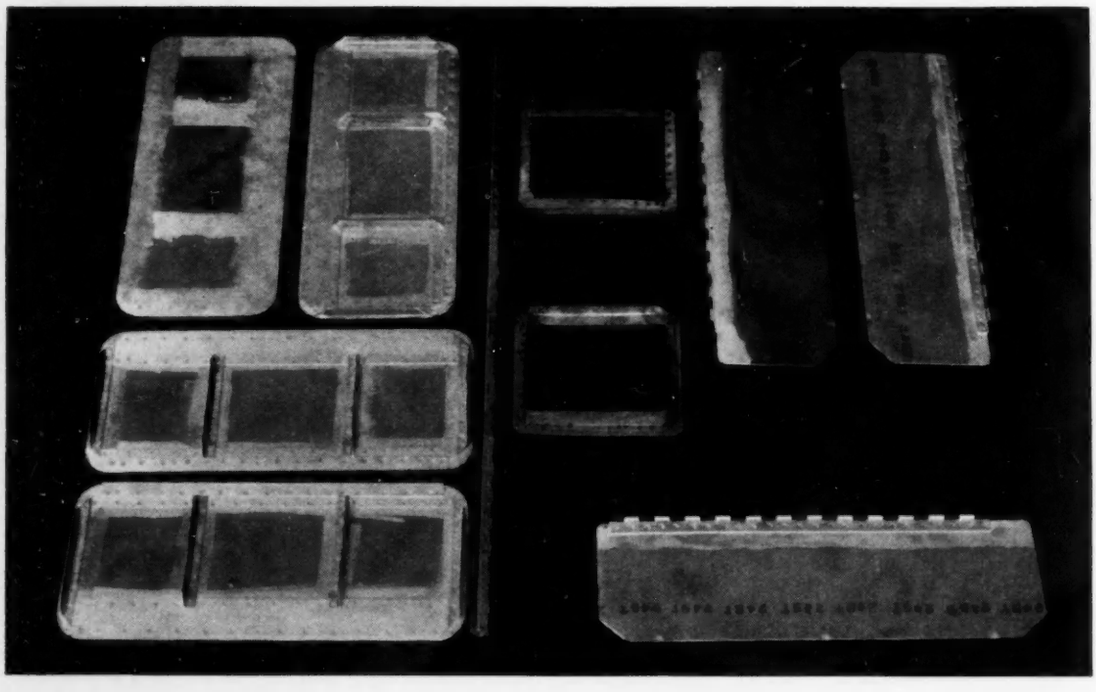


Fig. 11 – Inspection Doors, Reinforcing Flange, and Hinged Glass Retaining Channel

Doors approximately 16 in. long. 24ST aluminum alloy from 0.025 to 0.051 thickness. The areas from which the heavy oxide coating has been removed are discernible clearly.

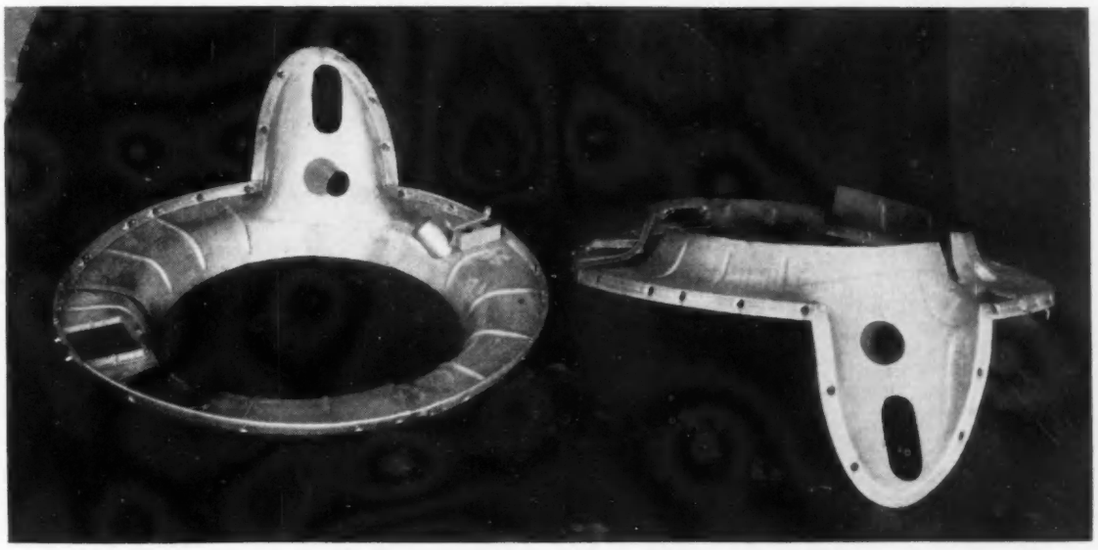


Fig. 12 – Shroud Ring

Approximately 44 in. in diameter. 0.018 to 0.031-in. corrosion-resistant (18-8) steel. Approximately 1000 single spots. Peripheral reinforcing band attached by intermittent roll welding, approximately 2500 spots. Punching and drawing of holes for fasteners done after roll welding.

There are here 13 basic materials shown as being spotwelded; several of these materials are divided into various tempers or degrees of hardness. Since these differences lead to substantial variations in the optimum welding conditions, it may be considered that each horizontal line represents a different material. As each thickness, in turn, represents a different welding condition, the 130 circles on this chart indicate that 130 welding set-ups must be made.

In addition it is customary to find two materials of different thickness welded together or to find three or more thicknesses joined by spotwelding; several different alloys are mutually weldable. The author has made no attempt to determine the actual combinations in use at present; it is doubtless conservative to state that 250 welding combinations are being used. No one manufacturer is covering the entire range of materials and gages shown on this chart, but possibly he will sooner or later. At the present time two different manufacturers are working over some 60 per cent of the ranges shown. Although some of the materials here shown are obsolescent from the aircraft viewpoint, new materials are being introduced continually and, where their characteristics make it practical, they are being spotwelded. Consequently this chart will grow in height and width rather than shrink.

Typical Production

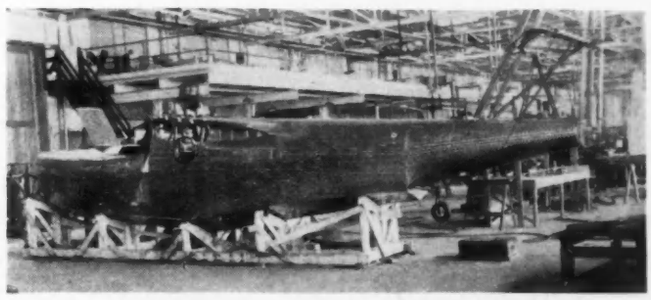
Figs. 10, 11, and 12 show typical partially or completely spotwelded assemblies selected from the production lines of various manufacturers.

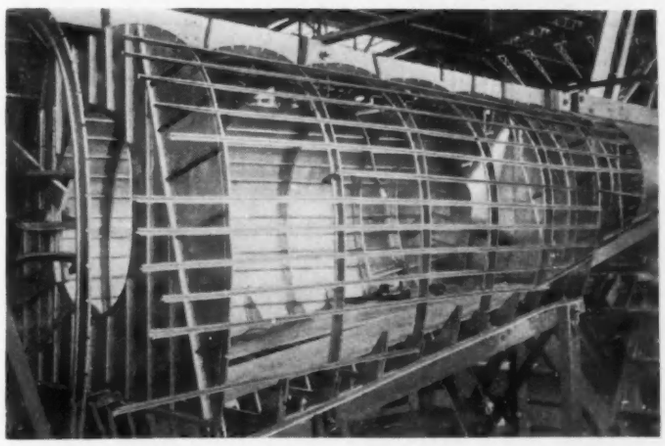
Figs. 13 and 14 show progress views of an experimental all-stainless amphibian recently completed by an organization that has pioneered this type of construction. Virtually the entire structure is sub-assembled and finally assembled by spotwelding. Although this is not a production job in the sense of having been built in quantities of five or more substantially identical units, it is ready to go in production and is shown here to indicate the extent to which spotwelding can be applied to large assemblies.

One manufacturer that has been using spotwelding of the aluminum alloys and corrosion-resistant steels on a production basis for some four years, averages about 15,000 spotwelds per airplane and, on some production models, over 25,000 spotwelds per ship are used. 25 per cent of this work is done at speeds of 500 to 1200 spots per min.

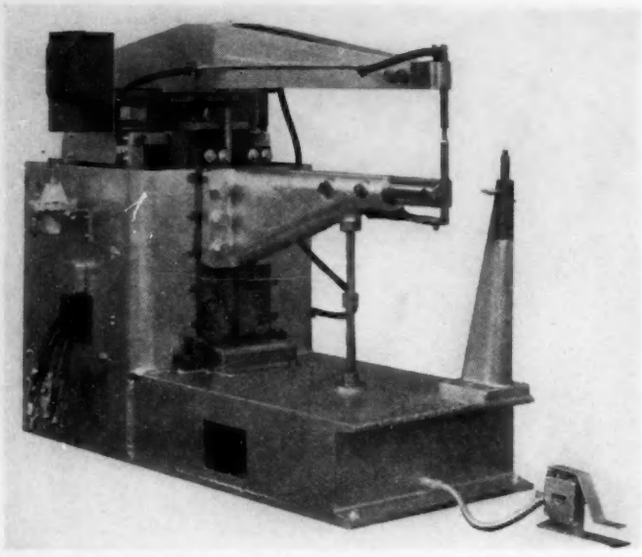
Spotwelding Costs

Spotwelding costs may vary over a wide range depending upon the materials being welded, the type of equipment in use, the complexity of the assembly, special tooling, and the type of welding desired. Certain materials, notably the strong aluminum alloys, require complete removal of the more or less tenacious oxide film before welding. Others of the aluminum alloys require partial removal of the film from all of the surfaces, or removal of all of the film from some of the surfaces; the stainless steels require removal of all foreign matter, such as pigments in identifying inks and paints, dirt-bearing oil or grease, and free dirt or dust.





Figs. 13 and 14 – Progress Views of an Experimental Amphibian Assembled of Stainless Steel by Spotwelding



Courtesy Federal Machine & Welder Co.

Fig. 15 – 300-Kva. Spotwelder, 36-In. Throat

The horizontal lower arm on this machine may be lowered about 1 ft. to double the clearance between upper and lower arms. For welding large work the pedestal arm shown at the right-hand corner of the step may be substituted for the horizontal arm, greatly increasing the mechanical range of the machine but at some expense of electrical capacity due to increased impedance.

The operating speed of spotwelders may vary from 30 spots per min. in the case of earlier types of equipment to 1500 or 1800 spots per min. in the case of well-built roll-welding equipment operating in conjunction with synchronous tube timers. The complexity or size of the assembly is obviously an important factor; it is not uncommon to find small but complex units that require several successive machine set-ups and actually more time in changing set-ups than in productive welding. Well-designed jigs and fixtures often increase output per man-hour several hundred per cent.

The type of welding required influences the operator's output; if, for reasons of appearance or of stress distribution, he must place his individual spotwelds with accurate spacings on predetermined lines, he cannot work as rapidly as when he may space and locate spotweld positions by eye.

Due to the preceding factors it is impossible to name an arbitrary figure as the "cost of a spotweld." Taking the production run of work with materials, thicknesses, and general design suitable for spotwelding, the costs per spot of welds made by the single-electrode method will range from 3.0 cents to 0.1 cent, with the average between 0.3 and 0.5 cent. On assemblies where roll welding (either intermittent or seam) may be used, the costs will run from 0.1 to 0.01 cent per spot.

The foregoing figures are for direct labor and electrical energy, assuming a rate of 1 cent per kw-hr. and a 10 per cent electrical efficiency. Equipment charges will vary widely with the type of equipment in use and with accounting methods. A small manually operated machine with a tube-control high-speed contactor, quite suitable for welding light gages of corrosion-resistant steels, costs less than $1000. A general-purpose single-spot machine with an electronic-tube timer, capable of handling medium gages of aluminum alloys, may cost $4000 or $5000. A heavy-duty high-speed combination single-spot and roll machine with an electronic-tube timer of sufficient capacity to handle the heavier gages of aluminum alloys may cost $6000 to $10,000.

Modern Equipment

Figs. 15, 16, and 17 show several spotwelding machines built in the last few years, specifically for aircraft work or for welding of aluminum alloys.

Certain features are now characteristic of all modern, general-purpose equipment:

(1) Operation is pneumatic, with electrically controlled valves.

(2) The arms are beam sections designed to give maximum rigidity consistent with the slenderness necessary to permit use of the machine in crowded quarters.

(3) The length of arm or throat and the spacing between upper and lower arms are adjustable or may be changed by substituting other parts.

(4) The transformer is situated so as to give minimum impedance losses for a given secondary circuit.

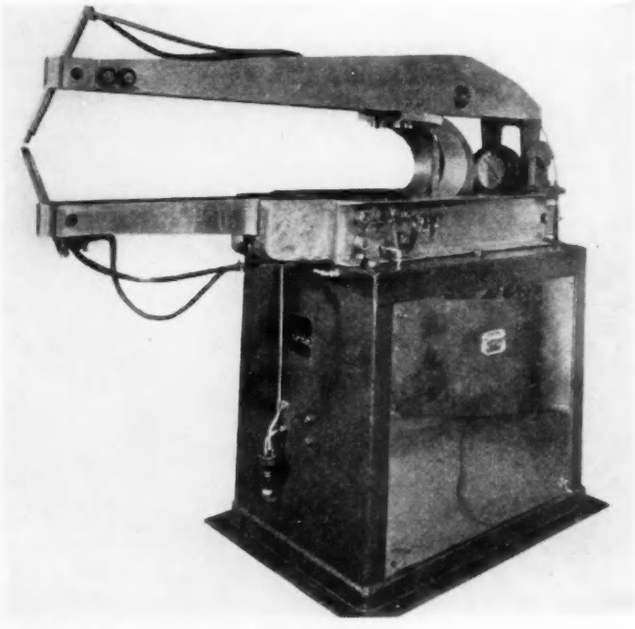
(5) The transformer itself is water-cooled, sometimes the welder arms are water-cooled, and invariably the welding tips are, or can be, water-cooled.

(6) Moving parts are designed for minimum inertia, or dash pots are provided to cushion the rapidly traveling mechanism at the end of the stroke.

(7) Electrical inching devices are used to permit raising and lowering the upper arm to clear stiffeners, flanges, and so on.

Although the present machines are incomparably superior to those of a few years ago, certain trends in design must be carried further and other design trends must be introduced before the aircraft manufacturer can be entirely satisfied. Some of these design trends are:

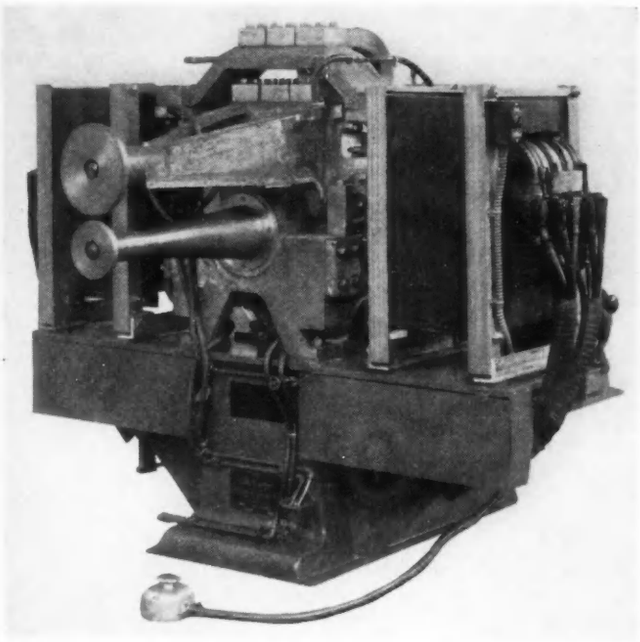
(1) All controls should be centralized as much as possible; operating controls should be duplicated for hand and foot in portable stations; and operating adjustments susceptible of



Courtesy Taylor Winfield Corp.

Fig. 16 – 600-Kva. Spotwelder, Approximately 48-In. Throat

Water-cooling tubes for both upper and lower electrode holders are discernible clearly. The capacity of this machine for work on small assemblies at heavy gage may be increased by substituting for both upper and lower arms interchangeable units that diminish the effective throat and secondary impedance, and permit greater electrode pressures.



Courtesy Federal Machine & Welder Co.

Fig. 17 – 400-Kva. Roll Welder, Approximately 36-In. Throat

In machines of this type, construction is simplied and impedance losses are reduced by mounting a pair of transformers symmetrically either side of the electrode arms. For seam or intermittent roll welding, this machine operates in conjunction with an electronic-tube timer.

being handled remotely should be grouped together, preferably in a portable unit.

(2) Mechanical flexibility and adaptability of the welder arms and of electrode holders should be improved greatly to minimize set-up time.

(3) Heavy-duty and expensive roll machines should be modified or redesigned to render them capable of single-spot work with reasonable adaptability.

(4) Roll machines operating in conjunction with electronic timers should be designed to give a predetermined spot *spacing* independent of roll speed, roll diameter, or variation in roll speed.

(5) Control and power circuits of electronic timers should be developed that will permit operation of two or more single-spot machines, working if necessary at different timings from the same electronic timer.

(6) A device should be developed to measure the Joule heat actually *developed in the work*. This device should be applicable to the problem of detecting instantaneously serious deviations from a pre-selected standard.

(7) Electrode materials should be improved. One of the most serious difficulties in spotwelding and roll welding of the aluminum alloys lies in the tendency of the electrodes to alloy with the work. To be satisfactory, a new material should have electrical conductivity at least 85 per cent of that of pure copper, should be as hard as possible while still remaining machinable, and should be incapable of alloying with aluminum or any of its alloying elements.

The Future

The best expression that the author can find to characterize aircraft spotwelding is "small-scale diversity and complexity." He has pointed out the extraordinary diversity of work that may have to be handled in the course of building just one airplane, and he has indicated the complexity of the individual set-up problems from the mechanical, electrical, and metallurgical viewpoints. The aircraft manufacturer seldom has the inclination to attack these problems from any angle but the one of turning out consistent production with equipment that is engineered for the job by specialists in the field. What he has done in the past in development of equipment and technique and in study of metallurgical problems has been done only as a matter of necessity in getting into an economical production basis.

A harvest, not rich, but probably satisfactory, awaits the manufacturer or manufacturers of spotwelding equipment that not only will give the aircraft industry the kind of equipment it needs, but also will furnish the basic information and technique that will permit the manufacturer to get into production rapidly and stay there with a profit.

Any attempt to predict the future course of spotwelding in the aircraft industry is futile. It is thoroughly established for assembly of unstressed parts and secondary structure. If and when corrosion-resistant steels are used generally for primary structure, spotwelding inevitably will become a major production method. If readily weldable aluminum alloys find their way into the primary structure or if new welding technique applied to present alloys satisfies necessary criteria, spotwelding will here find an important place. After prolonged gestation and painful childbirth, it now toddles about learning to use its hands while performing little tasks. Who knows? Will it remain a child, or will it soon be rudely shoving its older brothers and sisters aside and demanding the drumstick at the first table?

Discussion

Describes Current Controller and Electrode Material

—**E. W. Morris**

Engineering Division, Westinghouse Electric & Mfg. Co.

THE author states that "certain trends in design must be carried further and other design trends must be introduced. . . . Some of these are:

"(1) All controls should be centralized as much as possible . . . and grouped together.

"(7) Electrode materials should be improved. To be satisfactory, a new material should have electrical conductivity at least 85 per cent that of pure copper, should be hard as possible while still remaining machinable, and should be incapable of alloying with aluminum or any of its alloying elements."

Referring to the author's first suggestion, that of more centralized control, we observe that the operator of a spotwelding machine is concerned primarily with three adjustments:

(1) Electrode pressure.
(2) Length of time during weld.
(3) Maximum during weld current.

Adjustment of electrode pressure usually is accomplished mechanically and will not be commented on since I am interested primarily in those adjustments that affect the high-speed timing equipment.

The adjustment for duration of welding time is a simple control that has been available for some time on all electronic timers. This adjustment is made by one or two small dial switches and rheostats that can be mounted near the operator's position.

Referring to Fig. 7 of the author's paper, it will be noted that a coarse adjustment of the current during weld is obtained by a large number of heavy current switches on the switching panel. The connections are not shown on the diagram, but I can assure you that physically it is a bulky and complicated arrangement. These switches must be

adequate for handling peak currents of approximately 2500 or 3000 amp. during welds.

The modern Westinghouse Ignitron welding timer provides for the simple control of maximum welding current by means of a small adjustable rheostat that can be mounted for convenient operation by the operator. No switching arrangement is required, such as shown by the author in Fig. 6, to take up valuable space on or near the welding machine. The trend of spotwelder construction is to get the transformer as near to the electrodes as possible, and the elimination of the complicated switching for adjustment of welding current makes it easier to accomplish this design trend. "Heat control" on the Westinghouse Ignitron timer provides an infinite number of steps-in during weld currents, and the operator easily can make this adjustment in a very few seconds. (Fig. 7 in the last paragraph on page 107 should be referred to as Fig. 6.)

In answer to the author's request for new electrode materials, note that from the research laboratories of Westinghouse comes a new material that was developed for this very purpose. This material, known as Cupraloy, has 90 per cent of the conductivity of copper. It has a strength greater than cold-rolled steel, yet is machinable. These electrical and mechanical properties tend to make it an ideal material that does not fuse easily with the work nor become distorted due to enormous pressures applied to the electrodes.

Theory and Fundamental Problems Discussed

—Dr. H. E. van Thijn
Member, Royal Institute of Engineers

MR. BURNS' paper is indeed an interesting document. It gives us the present status of the technique in aircraft. The aircraft technique has grown so rapidly in the last five years that the process of spotwelding could not keep in step with its evolutions in other industries. However, I know a doctor who in ten minutes can age this child at least ten years if you will be good enough to give me your time for a diagnosis. Let us first give the baby solid legs and backbone, in other words, develop a relationship between the various values and variables involved.

The procedure of spotwelding outlined seems to miss an understanding of the physical principles involved. By applying the extended theory of Maxwell, it has been found that we can establish the equations necessary.

Predetermination of Resistance. – About 10,000 tests on different materials have proved that the resistance R does not depend on the gage of the material and can be expressed as:

$$\frac{1}{R} = \frac{k_1(D_1 + D_2)}{r_s}$$

where

r_s = the specific resistance of the material.
D_1, D_2 = the diameter of the upper and lower electrode respectively.
k_1 = an experimental constant independent of the material and gage.

It is interesting to note that neither the pressure nor the corrosion appear in this formula. This omission can be explained easily. The formula only applies when current flows, and these oxides have a negative resistance characteristic. The energy per operation:

$$I = \int \frac{i dt}{t}$$

I = can be obtained through cathode-ray oscillograms.

$$W = I^2 R t$$

R = resistance of spotweld. This value is not constant due to the positive resistance characteristic of the material used and to the negative characteristic of the oxide.

Thermodynamic considerations lead to:

$$W = \left(A_1 \frac{s d^2}{t} + A_2 s + A_3 \frac{d^2}{s}\right) k_2 (T_1 - T_2)$$

s = thickness of stock.
d = diameter of weld.
t = welding time.
T_1 = fusion temperature (absolute).
T_2 = room temperature (absolute).

$$A_1 = \alpha \sigma ; \quad A_3 = \frac{\rho}{8}$$

k_2 = a constant depending on unit system used.
α = specific heat of stock.
A_2 = thermal conductivity of stock.
ρ = thermal conductivity of electrodes.
σ = density of stock.

In this formula, W is a known quantity that can be controlled completely. We thus find a *relationship between the size of the weld, welding time, and energy input, which enables us to predetermine same.*

The strength of the joint depends upon the size of the spot; simple considerations of applied mechanics lead to further formulation in this instance.

Departing from theory in consideration of Mr. Burns' paper, at a recent survey of one of our largest aircraft companies, it was found that three fundamental problems hampered the general application of spotwelding. These problems have been overcome in workshops abroad in the past three years. No papers, however, were published perhaps due to that cover of secrecy which often makes many experimenters develop the same method. The problems involved were:

(1) How to obtain a predetermined strength.
(2) Proper designs of electrodes.
(3) How to obtain reliable welds, for instance, elimination of cracks and the influence of prevailing variable degrees of oxidation.

(1) According to the methods pointed out, Mr. Burns stated that insufficient shear and stress are obtained. Spotwelding so described has its limitations because only the welding of single spots is considered. Single spots always have to be distanced about ½ in. in order to prevent a short circuit through the last spot. On this basis a predetermined strength never can be acquired, unless it is very low.

Embossed or projection welding leads the way to every possible predetermined strength. It requires the embossing of the points before welding. Any combination of spots can be obtained. These combinations, which should be designed at distances of about ½ in., are welded in one operation. The electrodes are flat and square and do not show any adhesion.

Due to the fact that the mechanical pressure is transferred in the joints, only by those points that actually are going to be transformed in welds, mechanical pressure builds up very high – sometimes as high as 50,000 lb. per sq. in. This pressure eliminates practically the resistance of oxide layers, which decreases under pressure. Even thin paint coats can be allowed under certain circumstances.

(2) With regard to the design of electrodes, without doubt the best electrode material to be used is electrolytic copper. In 10 years of spotwelding, hardly ever has there been met a stock that could not be welded with electrolytic copper. "Mushrooming" can be prevented by efficient steel reinforcement. This material, providing it is polished properly, will show very little adhesion, even with stock, such as 24ST. Water-cooling is only then imperative when segregation of the stock is anticipated, for instance, with stainless steel.

(3) In order to obtain reliable spots that do not have to be torn apart each time and in order to find out how satisfactory they are for materials such as 24ST, special considerations are necessary.

About two years ago when spotwelding of aluminum alloys, such as 24ST, and some rare steel alloys began, irregular strength characteristics were found. X-ray photographs taken with Metalix apparatus showed irregular cracks in most spots. After considerable experimenting, these cracks could be traced to shrinkage in the spot due to very small expansion of the stock after welding. This difficulty was overcome by increasing the electrode pressure after the current flow had stopped. Sometimes, after welding with only ½ cycle, the pressure was increased 100 per cent and maintained for 10 to 20 cycles after the current flow. This method provides for slow cooling under pressure.

The oxidation of a stock depends on many known factors and might change considerably. Its definite solution is found in the discussion of problem (1).

This discussion covers a few of the fundamental problems in a schematic way, pointing I think, toward a brighter spotwelding future.

Present Limitations Pointed Out

—C. L. Hibert
Consolidated Aircraft Corp.

IN my opinion the advantage of spotwelding of aluminum alloys in aircraft work is mainly the difference in cost from that of similar riveted construction. This advantage is enhanced somewhat by appearance and streamlined surface. Mr. Burns has neglected to mention some disadvantages that prevent a greater saving from being realized.

First, we have a lack of production in the aircraft industry unless one wants to call 50 pieces, which usually are built in units of 5 or 10, production. After all, spotwelding is production equipment and, unless sufficient work of the same type is available, a large saving cannot be effected due to change-overs and delays in set-ups. When

over 1000 welds per hr. are banged out on assembly, which at the most may only have 500 welds, it does not take long to run off 5 assemblies.

At present only secondary structures of aluminum alloys may be welded due to the unreliability of spotweld construction and the inherent weakness in tension. Another limiting factor is that on Army and Navy contracts only two alloys are approved for spotwelding, namely, 52S alloy and Alclad. Spotwelding is restricted to these alloys from a corrosion standpoint. 52S alloy is an ideal spotwelding alloy as it is cleaned easily and 100 per cent joint strength may be realized. Sad to state it is of low strength and has cold-working properties, which further restrict its use. As for Alclad alloy it is difficult to spotweld and objections are heard against its use due to the necessary 10 per cent increase in weight because of lower tensile strength over that of non-Alclad alloys. It would have a distinctive advantage inasmuch as it would not be necessary to anodize, prime, and paint Alclad but, nevertheless, since anodizing, priming, and painting seem to be in order for non-Alclad alloys, they are put through the same process regardless of cost, and the advantage in using Alclad is lost. Of course, in commercial work these restrictions are lifted and more work can be designed for spotwelding and all of the aluminum alloys may be used.

It is unlikely that much stainless steel will be used in aircraft because there is not a sufficient supply of chrome in this country in case of emergency and because of difficulties in design from using the necessary lighter gages. If it is ever widely used it may be safe to predict entire airplanes of spotwelded stainless-steel construction.

Choice of material is essential to satisfactory spotwelding whereas in aircraft we are restricted to high-strength alloys which, in case of chrome-molybdenum and high-carbon steels, are not just the things to spotweld. The higher the carbon the more difficult it is to effect a ductile weld. When aircraft engineers stop to consider cost of construction and will select materials for spotwelding, we shall see row after row of spotwelding equipment.

When Mr. Burns included Fig. 7 he left himself wide open for attack. It is doubtful that any other worker will agree with his chart, not to infer that he is incorrect. What I mean to say is that there has been so much quibbling among different groups as to the variables to use.

My policy has been to set the pressure for aluminum alloys at 10,000 lb. times the thickness of the thinnest gage welded and set timing at 1, 2, or 3 cycles and adjust the current to give the optimum shear strength for spotweld because, after all, strength per spotweld is the criterion. Another point, let us forget all about ½-cycle welding and coordinate results.

Describes Control Equipment To Give Desired Features

—W. C. Hutchins
General Electric Co.

THE author states that moving parts (with reference to the upper-electrode assembly) are designed for minimum inertia or, when pneumatically operated machines are used, dashpots are provided to cushion the rapidly traveling mechanism at the end of the stroke.

Even though dashpots are used, it is still essential that the moving parts, which are rigidly connected together, have minimum inertia, or minimum weight. This requirement is important so that, as the weld progresses from the instant the current starts to flow until the current stops flowing, the electrodes will maintain pressure on the work and, consequently, good electrical contact. Furthermore, it is important to maintain an even pressure so as to complete the weld operation by forging the parts together. Should the entire pressure of the electrodes on the work be crested by a dead weight, such as a solid mass of steel or cast iron with no spring action, the metal will give under the weight of the electrodes as it approaches a welding temperature. The result is that, due to the inertia, the pressure of the electrodes on the work becomes relatively light, and the contact resistance between the electrodes and the work increases rapidly. The heavy parts would not "keep up" with the rate of welding. Pitting, flashing, and squirting of metal are likely to occur which actions, of course, damage the surface of the work and, at the same time, decrease the life of the welding electrodes.

The author states several of the desirable features that must be introduced before the aircraft manufacturer can be entirely satisfied. For instance:

All controls should be centralized as much as possible with duplicate operating controls for hand and foot in portable stations.

I assume that the author has in mind devices for changing the electrode pressure, adjusting the position of the upper arm of the machine, and also the time adjustment of the electronic control that handles the primary current of the welding transformer. Thyratron control units can be supplied with remotely mounted time-adjusting dials that are calibrated in cycles or half cycles of the power supply. This time adjuster can be mounted on a small panel with all of the other control push-button stations, and the complete operation can be made from one remote point. If the preferred arrangement and location of the controls are specified to the welder manufacturer when asking for bids on the complete equipment, I am sure the welder manufacturers are in a position to quote and furnish exactly what is wanted. The price would be only a little more than for the conventional arrangement.

So as to produce satisfactory seamwelding (roll welding), it is necessary to maintain constant speed of the work through the rolls, and also to repeat consistently the duration of current flow for each impulse of current. Therefore, assuming that for any one production job the speed is adjusted properly, it is then a simple matter to accomplish that which Mr. Burns desires, namely—the spacing of the spots. A Thyratron control unit is now available which, for seamwelding, has two dials calibrated in cycles of the power supply. One of these dials adjusts independently the rate at which the power impulses will be supplied to the welding machine and is adjustable in half-cycle steps. The other permits independent adjustment of the time that current flows for each impulse in half-cycle steps. To accomplish that which the author desires, and that is to adjust the spacing of the spots, the process becomes very simple with this new calibrated Thyratron control. Where the power supply is 50 cycles per sec., there are 3000 cycles per min.

Assume a speed of 40 in. per min. in the adjustment of the machine.
Assume 3 spots per in. are required.
$3 \times 40 = 120$ spots which the control must make each minute.
3000 cycles per min. divided by 120 impulses per min. which must occur, means that the sum of the "on" plus the "off" time for seamwelding must equal 25 cycles of the power supply.

By referring to the calibration chart provided with the panel, the dial can be adjusted for exactly 25 cycles.

Another dial is provided on this same panel that permits independent adjustment of the timing for each impulse of power. This timing may be adjusted from a minimum of ½ cycle up to 15 cycles or more.

Should the speed of the work through the machine change, it will be necessary to change the tap setting on the welder transformer, or to change the heat control, which may be accomplished by some other means (such as phase shifting of the Thyratron control) or the timing of the Thyratron control must be changed. Therefore, I believe it to be impractical to have a device to change automatically the rate of current interruption as the speed of the work through the rolls changes. This control can be accomplished, of course, by using a spotwelder type of control and a variable-speed initiating switch on the welding machine to initiate rapidly the welds at the speed that is desired. When a different diameter of the welding electrodes is used, the speed of the work through the welder will change. In this case a friction drive from the welding electrodes could drive a small-diameter mechanism which, with a speed-changing arrangement, could initiate the control every time it was desired to have an impulse of power.

With reference to the operation of several welding machines from one electronic control, we wish to advise that this job has been done in several instances. It is not a particularly difficult problem, nor is it particularly attractive. The expense of the necessary interlocks, contactors, and other devices necessary for interlocking of these welders on one control seldom can be justified compared with purchasing an individual control for each welder. The limitation in the speed of operation of each welding machine and other considerations have prevented the use of this method of controlling welding machines in General Electric plants where more than 70 Thyratron-controlled welders are being used.

For seam welding of automobile gasoline tanks there are a total of 20 welding machines being operated with 10 Thyratron controls. One Thyratron control provides pulsating power to a bus. The welding machines are operated independently of one another, two welding machines being connected to each Thyratron control. To start welding, the electrodes are brought down on the work, then a contactor closes, connecting the welder to the pulsating bus.

With reference to the desire for a device that will measure the Joule-heat (watt-seconds) actually developed in the work, we can give the author very little encouragement on this point. A so-called ampere-second consistency indicator, which merely indicates whether or not the product of amperes and time in the primary of the welding machine is the same for each impulse of power, has been developed and applied successfully. This indicator does not, however, give the result that the author desires. Neither is there any known method of doing so today. Several engineers in this country have developed some de-

vice that, according to their theory, would work. The theory being wrong results in a device that will not work.

Probably the best method known today of insuring consistent welds is to follow accurately the best known practices. Some of the most important ones are as follows:

(1) A welding engineer (or supervisor) who is well qualified to direct all welding operations should be appointed. Working with the design engineers, he can adapt the parts to resistance welding. Only through this practice can the full benefit of resistance welding be obtained.

(2) All operators should be instructed and trained properly.

There are several variables in resistance welding that must be controlled accurately for the most consistent results. They are:

(1) Electrode dimensions, material, contact surface, cooling, and pressure on the work.

(2) Surface and character of metal to be welded.

(3) Value of current.

(4) Character of current wave for each weld.

(5) Timing of current for each weld.

Items (4) and (5) are not controllable by ordinary means, yet they are of vital importance in producing good welds; they are of such importance as to justify the following discussion:

(1) The flow of electric current through a body that offers electrical resistance will generate heat proportional to I^2RT. Thus, it becomes obvious that the heat generated at the weld is proportional to I^2RT where I^2 is the square of the current. This relation holds true not only for the effective value of current over a period of time, but also for the instantaneous value of current. *Therefore the character of the current wave is of prime importance.*

(2) R is the contact resistance between the parts being welded and the resistance of the material itself. This is the location of the highest resistance in the secondary of the welder circuit. The electrodes are made of a material that will minimize the resistance between the electrodes and the work.

(3) T is the duration of current flow from the time the current starts until the final interruption is accomplished.

With a highly reactive circuit, such as is found in a resistance welder, the value of current that flows in the circuit immediately after the a.c. voltage has been applied depends largely on the point on the voltage wave at which the circuit is closed, all other factors being the same. If the circuit is closed at a point on the voltage wave corresponding to zero current (approximately at the power-factor angle of the load), the current during the first half cycle will be essentially the same as the sustained current throughout the weld, and represents the minimum transient point on the voltage wave. This method produces a constant rate of heating.

If the circuit is closed at the zero point on the voltage wave instead of the minimum transient point, the current during the first half cycle will reach a greater peak value – a transient condition – the value of which diminishes as the current flow continues. Thus, since heating is proportional to the square of the current, the weld will receive a different amount of heat in a given time with each different point of starting on the voltage wave. With relatively long timing this variable is of little importance; however, for high-quality and consistent welding with short timing, this variable must be eliminated.

The only positive method whereby the current to a welding machine can be made to start flowing at a predetermined fixed point on the voltage wave is by means of the all-electronic type of control, such as Thyratron welding control.

Since the heat produced in the weld is proportional to the time of current flow for consistent welds, it is essential also to have accurate control for the total time of current flow. This control also is accomplished with best results by use of the all-electronic control, such as Thyratron control.

I, therefore, emphasize the importance of the character of the current wave for each weld, and the accuracy of timing of the current flow for each weld.

In order to have consistent current flow at the time the weld is made, it is also necessary to maintain good voltage regulation. In the selection of the power supply for resistance welding, 460 or 575 volts is to be preferred over 230 volts. This voltage will permit the use of less expensive control for the same amount of power and, at the same time, will permit the use of a considerably less expensive supply cable from the supply transformer to the welding machine.

To illustrate, let us take the following example:

Assume the resistance welding load is to operate on a 10 per cent duty cycle, and that the welding machine is located 100 ft. from the supply line. Let us further assume that the spacing between the cables is 4 in. from center to center. The demand during weld is 550 kva. It is desired to maintain voltage over this 100 ft. length of cable within 5 per cent (from no load to full load). In the event of 220 volts, the current demand by the welder will be 2500 amp. and it will be necessary to use 2 cables, each of which will be of 2,000,000 cir. mils.

In the event of 440 volts, the current will be 1250 amp. and the cable required will be less than 500,000 cir. mils. In the case of 550 volts, the current demand would be only 1000 amp., and a 250,000 cir. mil cable would be sufficient.

The General Electric Co. has done a considerable amount of developmental work in providing a most suitable panel for controlling of resistance spot and seam welders used in the aircraft industry.

The outstanding features of this particular control are: Spot-length control in half-cycle steps.

(1) Welding-cycle-length ("on" plus the "off" time) control in half-cycle steps for seam welding.

(2) Direct tube control without the use of series transformers.

(3) Dead-front panel which mounts time-adjustment and oscillographic type of inkless cycle recorder, which permits making a record of the timing for selected spot and seam welds and provides a means of checking the calibration.

(4) A switch is provided to permit selection of the mode of starting for each current-flow period (antipole or unipolar) for either spot or seam welding.

(5) Heat control from essentially zero to 100 per cent maximum capacity of the welder by means of an adjustment which is located conveniently on the dead-front time-adjusting panel.

(6) All parts of the panel are readily accessible because of full-length doors on both the front and rear of the enclosing case.

(7) Auto transformer provided to adapt the control to various line voltages between 200 and 600 volts. This control is particularly suitable for manufacturers who are purchasing their first equipments and desire the greatest of flexibility. It always can be used as a basis for setting up production jobs, the data from this particular panel being used in the selection of new equipment which is to be purchased.

Complete descriptive material on these panels is now available. Several of these panels already have been installed and are controlling production welders.

With reference to the author's closing statements, I predict that, as did the automotive industry and the electrical industry find resistance welding a dependable method of fabrication, so will the aircraft industry. It is important that the users of the equipment realize the importance of proper supervision, training of operators, and the use of dependable welding equipment, including electronic timing and power control. By so doing, the commercial joys available through the use of resistance welding can be attained.

Author of "Polaroid" Answers Roper Criticism

VAL J. ROPER, in his discussion of the paper "Polaroid," by Edwin H. Land, published in the January issue of the S.A.E. JOURNAL, states:

"The order of the losses incident to the use of Polaroid is indicated by some relative pavement-brightness measurements that we made with Polaroid samples with diffuse asphalt, concrete, and specular asphalt and employing a conventional headlighting system. Calling the pavement brightness as measured through the clear windshield and with clear headlamps 100 per cent, those with polarizer and analyzer parallel at 45 deg. were 11 per cent, 8 per cent, and 17 per cent respectively for the three surfaces. Calling the brightness of a vertical diffuse surface 100 per cent, as illuminated by the conventional headlamps, that with polarizer and analyzer parallel at 45 deg. was 8 per cent.

"It would then follow that, for the same seeing as with present headlighting, we would require about ten times present bulb candlepowers – hence approximately ten times present wattages."

Replying to Mr. Roper's criticism, Mr. Land brings out the following very important point:

"Mr. Roper's calculations of the percentages of transmission through Polaroid and his further calculations of the horsepower required for adequate illumination with Polaroid equipment are based on tests which he carried out on a grade of Polaroid that has never been proposed for automotive use. We have no means of knowing exactly what material Mr. Roper used in his tests. We assume, however, that it was the only grade which has been generally available – the extremely dense material sold by the Polaroid Corp. for scientific purposes."

Engine-Temperature Control Factors

By H. E. Winkler
Vice President, Winkler Mfg. Co.

MANY comprehensive papers have been presented on the various phases of the cooling problem. Macy O. Teetor's paper[2] on "Cylinder Temperature" and L. P. Saunders' paper[3] on "Radiator Development and Car Cooling" are representative of these.

The treatment of heat in an automotive vehicle presents many complex technical problems but the customer, who understands none of the technicalities, is directly aware of the results. He judges by: (1) how long the engine performs well, (2) how much oil it uses, (3) how often the radiator needs filling, (4) how much noise the fan makes, and so on.

Throughout the entire cooling system, the basic problem is one of rates of heat flow. Temperature balances are reached only when the heat lost by a given spot or system equals the heat absorbed. To have a balance temperature at a safe point, the rate of heat loss must be such that the temperature differential between hot and cold medium need not be too great.

High water velocities are frequently necessary to "scrub" out points where steaming tends to occur. Water pumps serve not only as a circulator within the engine, but also as a train of dump cars hauling B.t.u.'s to the radiator. Water-pump capacity determines the temperature rise of coolant through the engine.

Corrosion in cooling systems is due largely to air being drawn into the coolant at the pump packing or seals. Fan noise is a problem not limited to passenger cars.

THERE have been many most comprehensive papers prepared on the general subject of engine cooling.

In Stanwood S. Sparrow's S.A.E. paper on "Problems in the Development of a High-Speed Engine,"[1] he pointed out numerous devastating results directly or indirectly affected by heat not under control.

Macy O. Teetor's paper on "Cylinder Temperature"[2] presented much valuable data from laboratory research in which the difficulties were analyzed minutely.

L. P. Saunders' presentation entitled, "Radiator Development and Car Cooling,"[3] carried the consideration of the problem from the source of absorption, the engine, to the means for dissipation, the radiator.

Taken as a whole, the treatment of heat in an automotive vehicle presents many angles which in themselves are very complex. The customer who ordinarily does not understand the technicalities of the heat problem is affected in many ways by it. The results, direct or indirect, from the handling of the waste heat in a vehicle have a very real bearing on: (1) how long the engine performs well, (2) how much oil it uses, (3) how often the radiator needs filling, (4) how much noise the fan makes, (5) how long the fan belt lasts, and so on.

Customer satisfaction on all of these points demands attention beginning with the first design lines on the drafting board.

Although materials, conditions, and temperatures entering the cooling problem on a given vehicle vary widely, there is one fundamental relation that exists wherever there is heat flow. We know well that it is necessary to dissipate by the radiator an amount of heat that is equal to the heat absorbed by the coolant in the engine. It is also obvious that the rate of dissipation determines the final temperature of the coolant. This is to say that, if the rate of dissipation is too slow, then the coolant will rise in temperature to a troublesome degree.

This same situation exists at any spot across which there is a temperature differential. The temperature of the spot will approach the hot side until its potential above the cold side will produce a rate of heat egress equal to the rate of heat absorption.

The problem, therefore, is basically one in which a rate of

[This paper was presented at the Annual Meeting of the Society, Detroit, Mich., Jan. 11, 1937.]

[1] See S.A.E. TRANSACTIONS, February, 1935, pp. 58-69; "Problems in the Development of a High-Speed Engine," by Stanwood S. Sparrow.

[2] See S.A.E. TRANSACTIONS, August, 1936, pp. 328-332; "Cylinder Temperature," by Macy O. Teetor.

[3] See S.A.E. TRANSACTIONS, December, 1936, pp. 496-516; "Radiator Development and Car Cooling," by L. P. Saunders.

heat loss must be obtained that will prevent the hot-spot or surface from reaching a damaging temperature.

Final water temperatures, satisfactory in themselves, do not represent a satisfactorily cooled engine. Only the fact is represented that, at one point of heat transfer, the rate of heat egress is satisfactory.

Localized hot-spots within the engine, usually the cause of much of the bad news we hear about rings, pistons, oil consumption, and so on, assume different magnitudes of importance at different throttle settings and engine speeds. Hot-spots around cylinders complicate the "packing problem" and, in the cylinder-head, usable compression ratios are affected.

We have an interesting report regarding investigation on a European engine. A hot-spot of known existence at the upper end of a cylinder barrel was found to have less damaging effect at an increased engine speed and correspondingly increased power output.

It was found that an extremely stagnant condition in water circulation at low engine speed changed to one of considerable velocity at the higher pump deliveries, accompanying higher engine speeds.

In other words, the requirement for an improvement of condition in this case was supplied by increasing the heat-dissipation ability of the wetted side of the hot wall, so that the wall temperature did not rise to a point sufficiently above the boiling point of the coolant that trouble resulted.

In terms of design thinking, this requirement means that sufficient water volume is necessary to absorb the heat incident upon it. It further means high water velocities in the case of small passage areas or large passage areas in the case of low water velocities. It has been found, however, that the scrubbing effect of high impingement velocities is frequently necessary to eliminate a steaming condition irrespective of the size of the water column.

Although steaming points are admittedly a result of the engine design, the evil cannot be divorced completely through redesign. Cylinder designs, ideal from the standpoint of temperature only, usually are loaded with production, service, and cost problems to the extent that a compromise with undesirable temperature conditions makes the most commercial result.

Factors That Improve Cooling

Many things can be done, however, that result in the improvement of general conditions and that are entirely feasible. Full-length water jackets, sufficient space around valves and between valve centers, sufficient distance between cylinder-barrel centers, and the reduction to a minimum of areas f walls that have hot gases on one side and that do not have coolant on the other, are some of these things. Much attention should be given to the location of cylinder-head studs to avoid unnecessary deformation of the cylinder casting, along with the foregoing considerations.

The water pump, after it has served its purpose of providing internal circulation of coolant, then acts in the capacity of a locomotive for a train of dump cars hauling B.t.u.'s to the refuse-reduction pile which, in this case, is the radiator. Since the pump is not a dissipator, it does not lose heat, but the magnitude of the dissipation ability of the radiator core is dependent upon the pump capacity.

The heat input to the coolant by the engine raises the temperature of the coolant passing through it. If the coolant is water, the temperature rise through the engine is equal to the B.t.u. absorbed divided by the pounds of water circulated.

If the coolant is a 50 per cent alcohol solution which has a specific heat value of 0.8 and a specific gravity value of 0.9, the temperature rise through the engine would be approximately 40 per cent greater than with water ($\frac{1}{0.72} = 1.4$). Since the pump capacity by volume is less with the light solution, the temperature rise through the engine is still further increased. It is fortunate that this is a winter solution when the radiator-temperature problem is greatly reduced by low ambient air temperatures.

The water pump's job, external of the engine, is to keep the radiator hot. Failing in this function, best radiator efficiency is not obtained.

Radiators lose heat almost entirely by convection. This method means that the heat loss is proportional to the differential in temperature between hot radiator surfaces and the cooling air. Disregarding the effect of the thermal conductivity of the metal, the rate of heat transfer from radiator to air is nearly proportional to the differential between the average radiator temperature and the cooling air.

This temperature rise through the engine, which is the same as the temperature drop through the radiator core, therefore, determines how far the end points, top and bottom, are from the average. A low-capacity pump producing a drop through the radiator core of 20 deg. fahr. has a top tank temperature 5 deg. fahr. cooler when the water circulation is doubled and a 10 deg. fahr. drop produced. The increased cooling so obtained is on a very inexpensive basis. The cost of the pump is not necessarily increased, and the extra horsepower expended usually is of no consequence.

It is obvious that, although further increase in water circulation would still further lower the top-tank temperature, the law of diminishing returns becomes evident. Doubling the circulation, thereby reducing temperature drop from 20 to 10 deg. fahr., netted a reduction in top-tank temperature of 5 deg. fahr. Redoubling the circulation would change the drop from 10 to 5 deg. fahr., and only 2½ deg. fahr. improvement in cooling would result.

A drop of around 10 to 12 deg. fahr. seems to be the ideal commercial result, and most vehicles today are close to this figure.

The corrosive effect of the coolant on the metal parts which come in contact with it has presented certain difficulties. All metals are more or less solvent in water. It is said that before a metal can enter solution, however, some other element already in solution must be displaced.

Iron immersed in water displaces hydrogen as it corrodes. The hydrogen is deposited as a film on the surface of the iron where it would tend to prevent further corrosion were it not scrubbed off by the water velocity.

Wherever the coolant is allowed to take on air or become aerated, the hydrogen film is removed by the oxygen dissolved in the coolant. The rusting action, therefore, progresses freely, and the rust so formed is deposited throughout the cooling system and in the radiator. Cooling efficiencies then fall off because of the insulating effect of the rust deposit.

Much aeration originates from leaky pump packing or seals. Since water-pump impellers receive the coolant in its most aerated form and get the least protection from any film because of their velocities, corrosion of these parts has been common.

Coolants such as glycerine, ethylene glycol, solutions of soluble oil, and so on, which are of an "oily" nature, greatly

retard engine and impeller corrosion. Presumably, they place a protective film over the iron parts, thereby preventing the iron from going into solution.

With water and solutions of alcohol, the corrosive problem and its effect on cooling demand that the pump packing, or seal, admit a minimum of air. In our water-pump work we have found that the amount of air drawn into the coolant greatly affects the life of the impeller and the amount of rustiness inside the engine.

The use of a bronze impeller eliminates impeller difficulties, but it does not reduce the amount of trouble caused by the rust deposits in the radiator core.

Water-Pump Design

Several years ago there was a rather sudden change in water-pump location from the side of the engine where it was driven by an accessory drive shaft or triangular belt drive, to the "front end" where it was placed in combination with the radiator cooling fan. Two reasons prompted this change:

The engine was "cleaned up" and there was the attraction of a considerable saving in manufacturing costs. Frequently, it was necessary to move the pump from the side to the front to make room for other necessary accessories, such as larger generators, air compressors, and so on.

Unfortunately, however, fan-pump units were produced that were not provided with as satisfactory bearings as either the original fan or pump, although the new unit was expected to perform the duty of both old units. Limited space also frequently precluded a good stuffing-box design.

Enough trouble in service arose from designs of this type that several manufacturers went back to the side-pump arrangement. The rest, to quote a well known automobile engineering executive: "changed every six months in an endeavor to eliminate bearing trouble and stuffing-box leakage."

During the past several years, however, the quality of front-pump units, as well as side-pump units, has increased and today exceptionally well-built fan-pump units are in production, many of which use automatic seals in place of the conventional packing arrangement of several years ago.

Research work reveals that there are several fundamental requirements for a successful seal design. They are:

(1) The pump shaft must revolve on its axis and stay that way. This requirement means anti-friction bearings or excellent plain-bearing construction.

(2) The sealing face must be driven positively in the plane of seal. This requirement is necessary to avoid "lifting-off" and chattering.

(3) Seal-face materials must operate inside the pump, without lubrication, in any coolant, and without appreciable wear.

(4) Sealing-face pressures must be within predetermined limits and stay that way in operation. This requirement means that members of the seal assembly must not adhere or "stick" to the pump shaft. Such stickiness makes the sealing pressure erratic which, in turn, produces erratic seal operation.

(5) The sealing arrangement must not leak an appreciable amount of air. This requirement usually means rather high sealing pressures which further emphasize the need for free movement of sealing members that are made from the proper materials.

Fig. 1 shows a typical front-end pump design which employed one ball bearing. However, with this design the "wet-end" plain bearing wore, the packing leaked, and results were generally unsatisfactory. Fan-blade breakage frequently accompanies looseness in wet-end bearings. This trouble is due to the gyroscopic stresses imposed on the rotating parts by a "wobbly" shaft.

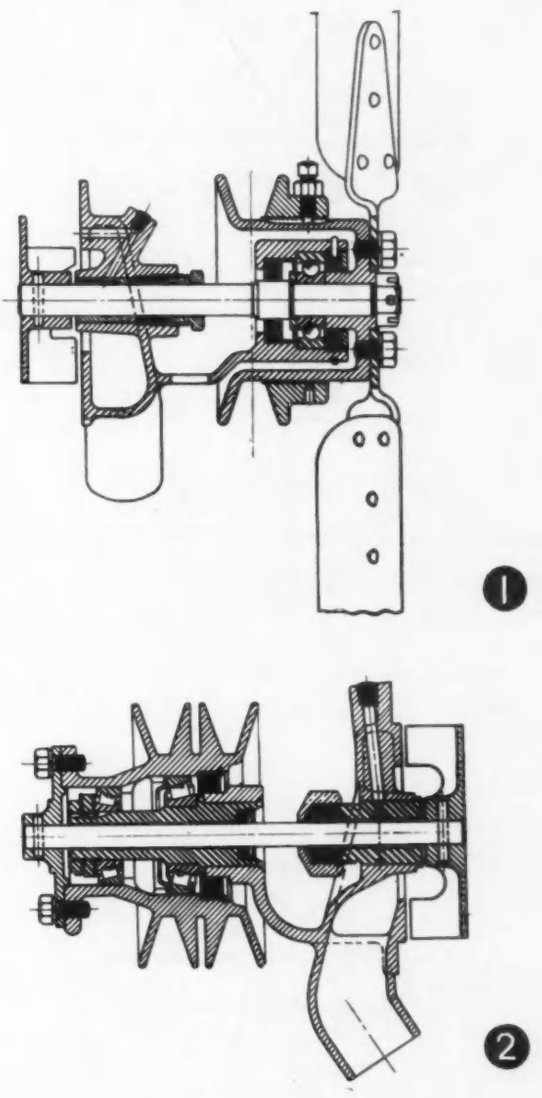


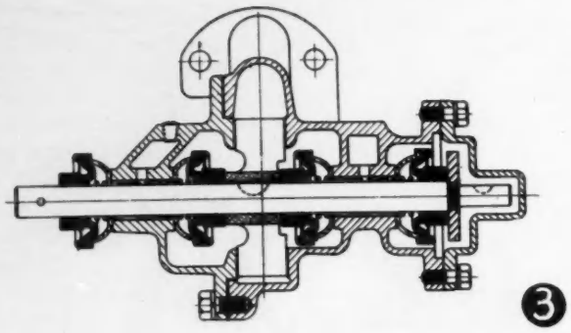
Fig. 1 – Typical Front-End Pump Design with One Ball-Bearing

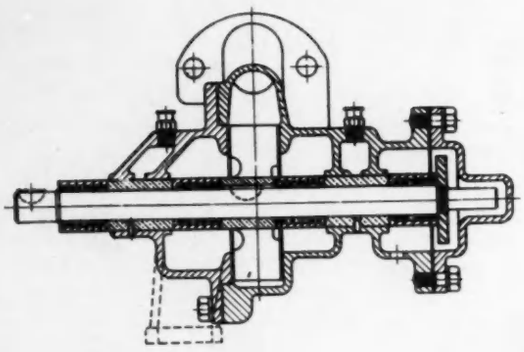
Fig. 2 – Tapered-Roller-Bearing Pump Design

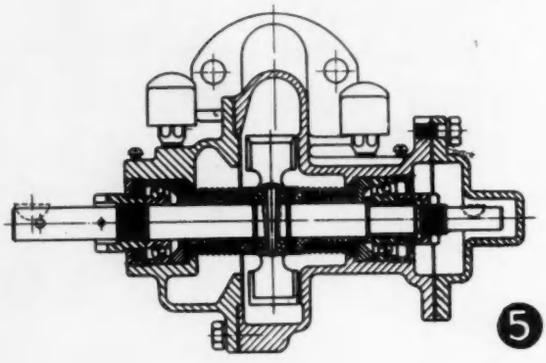
Fig. 2 is a tapered-roller-bearing design intended to eliminate all belt load from the wet-end bearing. This arrangement is an improvement over the first design (Fig. 1), but the sealing problem was not solved satisfactorily. Shaft packing has been a constant source of trouble. Operators tighten packing units until they wear the shaft, which wear aggravates the packing problem. The use of fancy material in the shaft helps conditions but raises production costs.

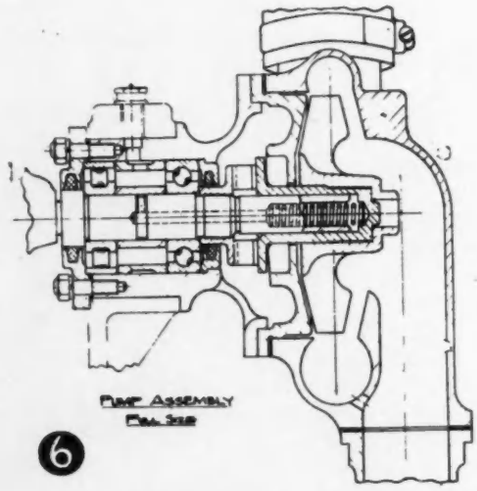
Too frequently, pump leakage is blamed on the packing arrangement only when it really is the result of the pump-shaft-bearing arrangement. Conversely seals, not good design in themselves, usually give creditable performance if the shaft is on good bearings.

The next several figures show various seal designs – some good – some bad.





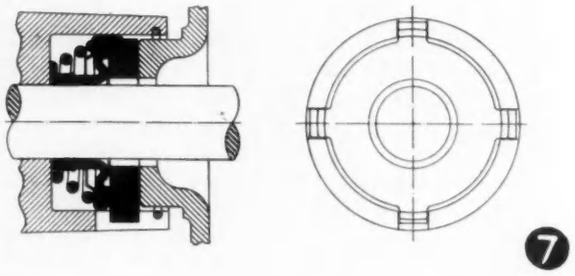


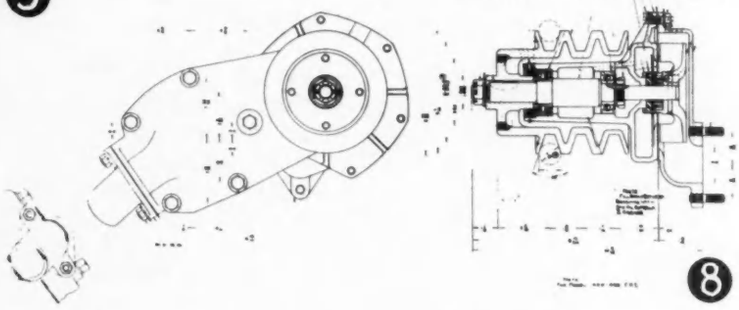


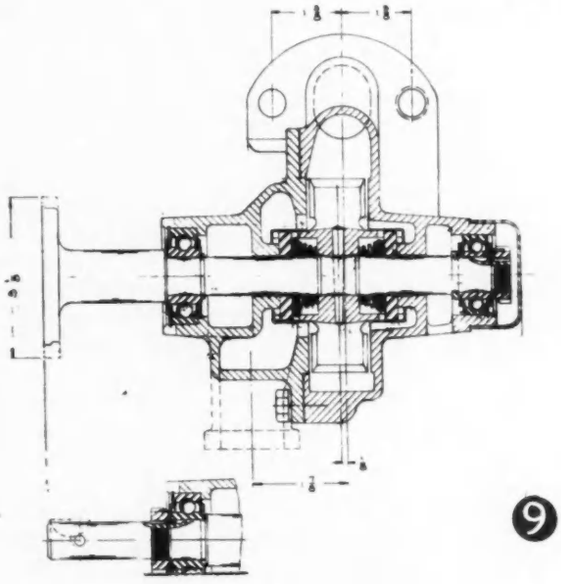
Figs. 3 & 4 – Pumps with Poor Seal Design

Fig. 5 – Pump Design with Copper Bellows that Unit-Seals at Each End

Fig. 6 – English Pump with Carbon Seal Member







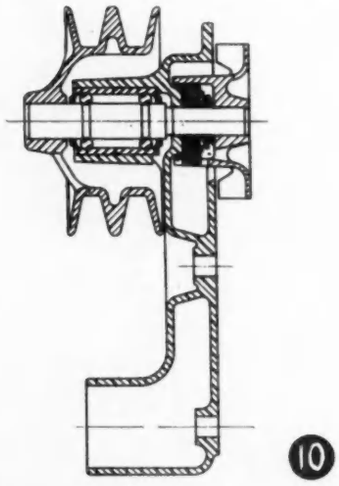


Fig. 7 – Satisfactory Seal Design

Figs. 8 & 9 – Typical Applications of Seal Shown in Fig. 7

Fig. 10 – Pump Design with Integral-Type Ball-Bearing and Shaft Assembly

The design shown in Fig. 3 was unsatisfactory because the sealing face was not driven positively and in the plane of sealing. The seal chattered and leaked. Also it was too large for many installations. It did, however, eliminate the necessity for any sliding on the shaft, the movement being taken in the rubber bellows.

The design shown in Fig. 4 also was unsatisfactory because of not being driven in the plane of seal. In addition, it would not slide on the pump shaft with any degree of constancy. The seal was small in diameter, however.

Fig. 5 illustrates a design that attempted to avoid the disadvantages of both the previous two designs (Figs. 3 and 4). It employs a copper bellows instead of rubber. It does not require sealing on the shaft. The design hoped to lower the relative velocities of the sealing surfaces. The necessity for proper wearing materials had become obvious from experience with the previous designs. The seal unit-seals on both ends.

Fig. 6 shows an English design of considerable merit but very expensive. The material in the seal member was carbon. Subsequent tests indicated that carbons of certain grades were excellent as a sealing-ring material.

Much research work evolved the design of Fig. 7 used in a number of production pump requirements. It satisfies the requirements of a good seal, being driven in its sealing plane, it is not affected by sticking on the shaft, and the materials are satisfactory. It is compact and not complicated.

Good typical applications of the previous seal (Fig. 7) are shown in Figs. 8 and 9. Note the ball-bearing arrangement on the shaft. Successful sealing requires good bearings.

Fig. 10 shows a very compact pump design in which the integral-type ball bearing and shaft assembly is used. This general construction is gaining favor on applications where bearing capacities need not be particularly large. The bearing is sealed permanently, no additional lubrication being necessary.

Anti-friction bearings are expensive, and we have worked out several installations on plain bearings lubricated from engine oil, which are giving excellent service. One of these installations is shown in Fig. 11. Oil is thrown into the bearing chamber from the drive gear and taken into the bearing through the distributor-drive-gear opening into the bearing. Drainage from both ends of the bearing is back to the engine sump.

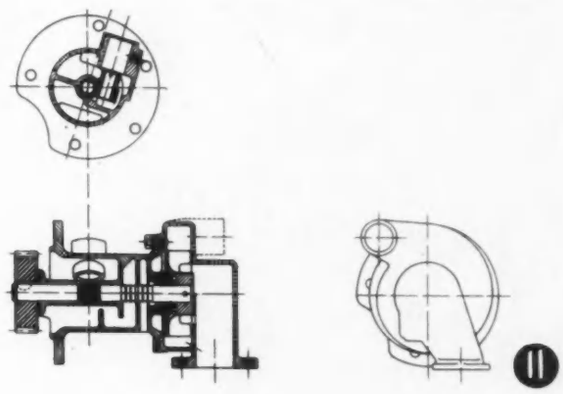
Fig. 12 shows a plain-bearing arrangement similar to Fig. 11 with a through shaft. Since it is impossible to get the splash-action lubrication on the outboard bearing, a wool-packed bearing of the type used on electric motors is employed. The arrangement is performing excellently.

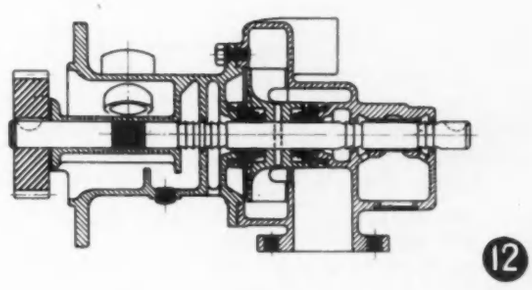
An interesting seal design is illustrated in Fig. 13, in which the impeller is a sealing member; it is driven by keys on the shaft and held in sealing contact with the pump body by the action of the spring inside the hollow spindle, as shown. This scheme of sealing is now used on one large production vehicle.

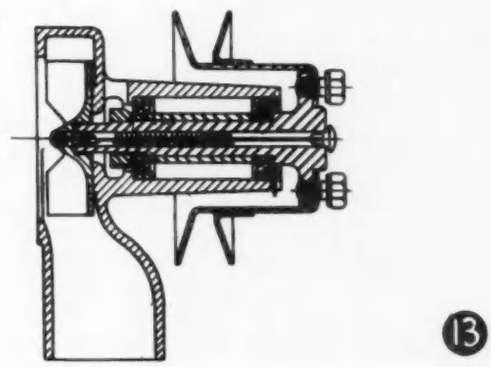
Fig. 14 shows a design in which the carbon sealing face is stationary and the rotating sealing face is the hub on the impeller. In all respects, it is a design similar to that shown on Fig. 7, with the exception that the relationship between stationary and rotating members is reversed.

Apparently the modern demand for noise reduction is doing more to produce good fan-design conditions than any demand ever made solely on the basis of efficiency.

It is difficult to discuss fan efficiency on a vehicle from the







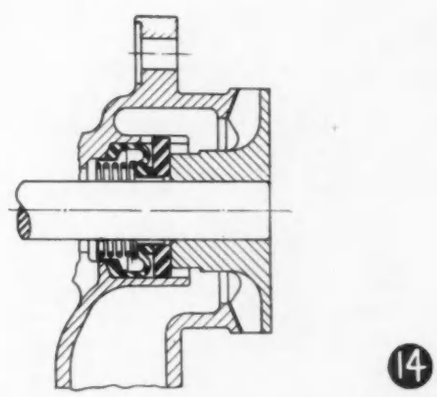


Fig. 11 – Design with Plain Bearings Lubricated from Engine Oil

Fig. 12 – Plain-Bearing Pump Design with a Through Shaft

Fig. 13 – Seal Design in Which the Impeller Is a Sealing Member

Fig. 14 – Seal in Which Carbon Face Is Stationary and the Rotating Face Is the Hub of the Impeller

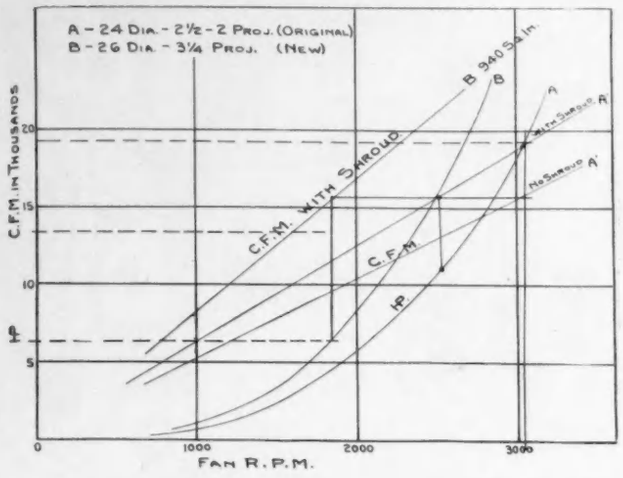


Fig. 15 – Air Delivery and Horsepower Required of Old and New Fan Set-Ups

fan standpoint alone. As a matter of fact, any and all fans of reasonable design that perform similarly under a set of fixed conditions with respect to diameter, speed, core specifications, and location will have efficiencies surprisingly alike.

When, however, these fixed conditions can be changed in the right direction, very real improvements in efficiency are possible.

Taking a specific case for example, a bus was being redesigned so that there was considerable leeway allowed in the selection and arrangement of the fan and radiator core. The engine previously had been cooled by a 750-sq.-in. frontal area core, and a 24-in. diameter high-capacity fan running 1.33 times engine speed. Under these circumstances, the fan required 19.3 hp. at a governed engine speed of 2300 r.p.m. Because of space limitations, the fan was not shrouded. On the new design, provision was made for 940-sq.-in. frontal area core, and a 26-in. diameter fan with a shroud.

A fan with wide flat blades was made for the new arrangement. The new fan was inherently a lower capacity unit, although having better efficiency characteristics than the original fan.

Fig. 15 shows the relative performance of the new and old set-ups with respect to air delivery and horsepower required

The original fan as shown on curve *A* gives air delivery of 15,700 cu. ft. per min. at a fan speed of 3050 r.p.m. requiring a hp. input of 19.3 at this speed.

Curves *A'* show an increase in delivery accomplished merely by the addition of a shroud without adding to the power consumption.

Curve *B* shows the new fan behind the 940-sq.-in. core with shroud delivering 15,700 cu. ft. per min. at 1840 r.p.m. the hp. requirement being 6.2, indicating a permissible engine-fan-drive reduction of from 1.33:1 to 0.8:1.

A number of factors contribute to this remarkable reduction in horsepower for an equal air delivery. The addition of the shrouds increased the air flow 20 per cent without changing the power consumption. This addition allows a decrease in fan speed and a consequent reduction in fan power requirement for an equal air flow.

In almost every case, shrouds are particularly desirable, except that they do not always effect advantages as great as in this case.

With the increased core area, the velocity through the core was decreased from 3020 ft. per min. to 2420 ft. per min. for a volume of 15,700 cu. ft. per min.

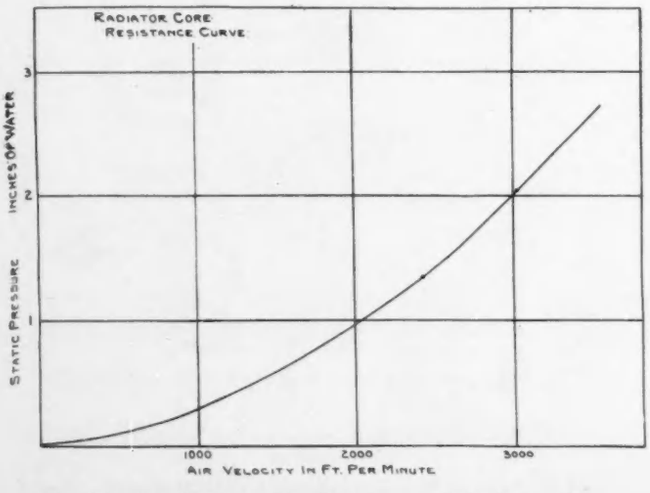


Fig. 16 – Air Velocity Vs. Resistance of Radiator Core

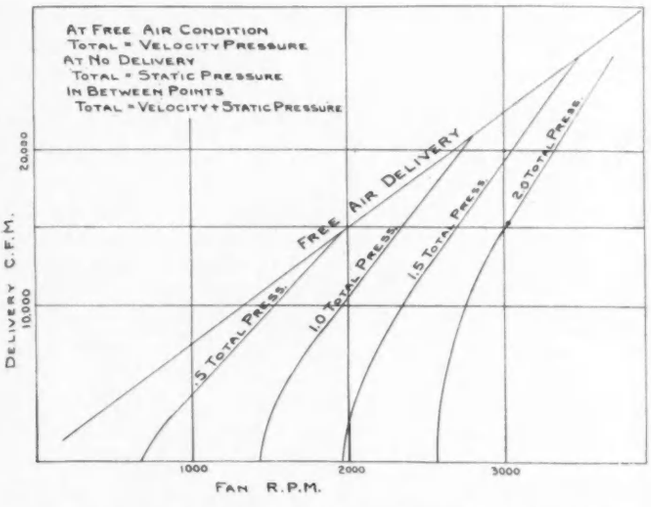


Fig. 17 – Fan R.P.M. Vs. Air Delivery at Varying Resistance Pressures

Fig. 16 shows that this reduction in velocity decreased the static pressure resistance from approximately 2 in. of water to about 1.35 in.

All fans fall off rapidly in delivery against increase in static resistance. Conversely, there is a considerable increase in the air delivery due to the reduction in static resistance. Fig. 17 illustrates this point.

The reduction in velocity allows an increase of the final temperature of the air leaving the core as shown in Fig. 18. This temperature increase under one set of given conditions amounted to 9 per cent.

Fig. 19 shows the two fans plotted against engine speeds with the fan drive ratios of 1.33:1 and 0.8:1, respectively for curves *A* and *B*. These horsepower curves show the great saving effected by this change in fan and core design.

Naturally, there will be a considerable increase in fan-belt life under the low-horsepower conditions as the drive problem is simplified greatly.

Power consumption and noise are roughly in the same proportion. There also is some correlation between noise and tip speed. In this case the tip speed was reduced from

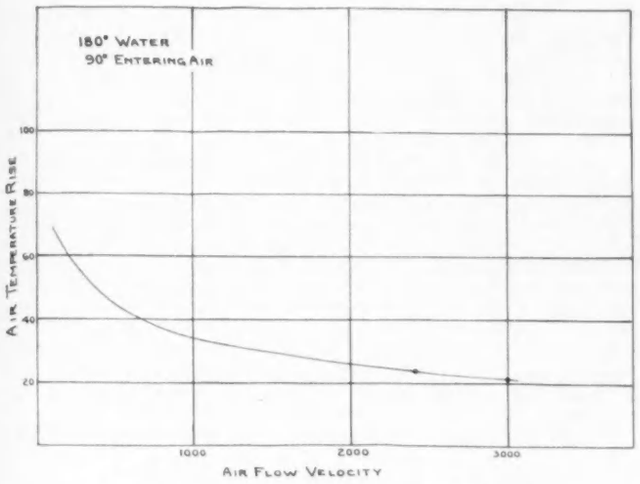


Fig. 18 – Temperature Rise Vs. Air Velocity

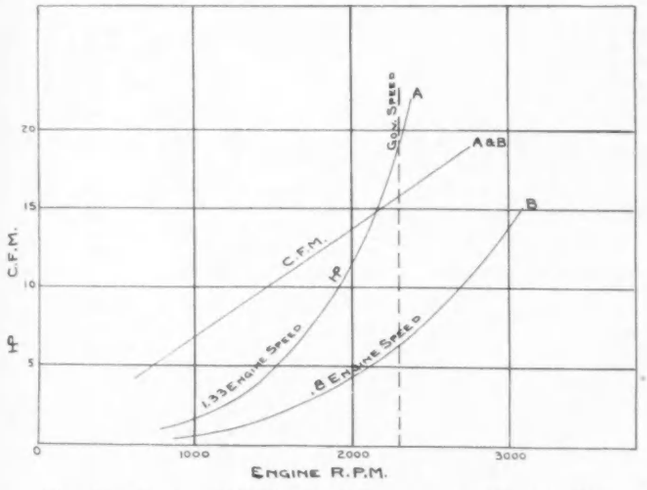


Fig. 19 – Engine R.P.M. Vs. Horsepower with Air Delivery Constant for Two Fans

19,160 ft. per min. to 12,500 ft. per min. The reduced power and reduced tip speed in the latter set-up over the former produced a very satisfactory reduction in fan noise volume, as well as a lowered pitch.

It is hoped that this paper will have brought out some points that are valuable in a practical way. Many cooling difficulties have been prolonged because, for some reason, good or bad, little has been done to improve the fundamental points.

Those of us who spend much of our time concentrating on the various phases of the cooling problem have entered our plea in the past and are continuing to do so – that the cooling problem may be considered along with the other major requirements of a successfully operating powerplant or vehicle. We have tried to get the same attention applied to the cooling problem with respect to space allotment, adequacy of bearings, use of correct materials, and so on, that would be applied to other problems.

Passenger-car designs change from time to time, and the opportunity to arrive at some of the points we would like to see adopted presents itself at the time of change. For instance, with the present chassis design with the motor moved forward over the front axle and the grille far to the front of the radiator, it is possible that sufficient room for satisfactory blade projected widths, fan-belt drives, bearing arrangements, fan discharge, and so on, be provided for. Some manufacturers have included these points in their changes. We hope that more will include them at the time of future changes.

Discussion

Methods for Controlling Jacket-Water Temperature Reviewed

– L. P. Saunders

Harrison Radiator Corp.

TO quote the author, there have been many most comprehensive papers prepared on the general subject of engine cooling. I wish to concur most heartily with Mr. Winkler's thought so far as Messrs. Sparrow's and Teetor's papers are concerned, which papers have to do particularly with various specific contributory causes of difficulties encountered with cooling systems as a whole. However, although Mr. Winkler's paper contains much valuable information with reference to the design of specific parts, I would like to take this opportunity to present some comments on the various types of control apparatus that have been and are in use today to insure that a minimum jacket-water temperature will be maintained without the detrimental results that go hand-in-hand with low jacket-water temperatures.

Thermostats, the general design of which does not have to be elaborated upon, are so reliable today that, for all practical purposes, their life can be conceded to be that of the life of the car. The exceptions to this statement, of course, prove the rule.

To run briefly over the various types of water temperature controls, there are shutters operated both manually and thermostatically, there are thermostats which are used for bypassing the water around the jacket, short circuiting the radiator until the control temperature is reached, and a blocking type of thermostat installation in which the radiator flow is definitely shut off until such time as the control temperature is reached.

In addition to these methods, there is the old thermo-syphon type of system which maintains the water-outlet temperature at approximately 160 deg. fahr. +, and various types of evaporative cooling systems.

The desirability of maintaining a predetermined water-outlet temperature regardless of air temperature, load, and speed is shown in Fig. *A*, which depicts the maximum horsepower curve of an engine at various speeds together with a complementary curve showing the horsepower required to drive the machine to which the engine is fitted, on

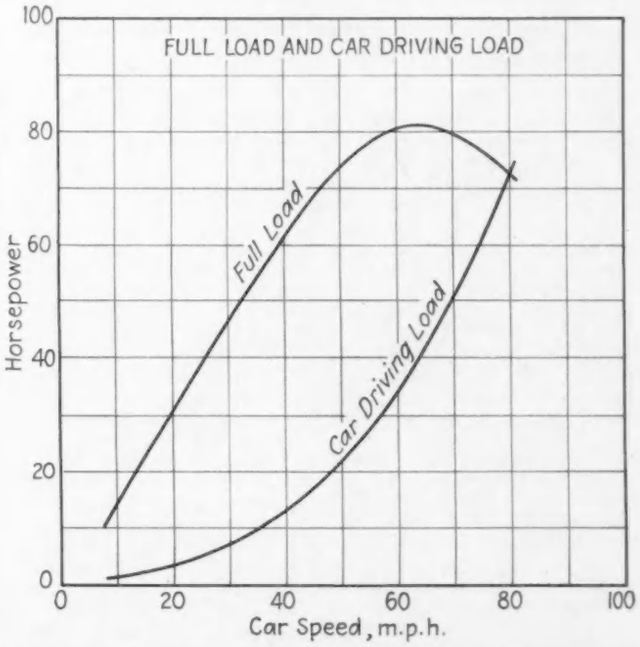


Fig. *A* – (Saunders Discussion) Horsepower Curves at Various Speeds – Full Load and Car-Driving Load

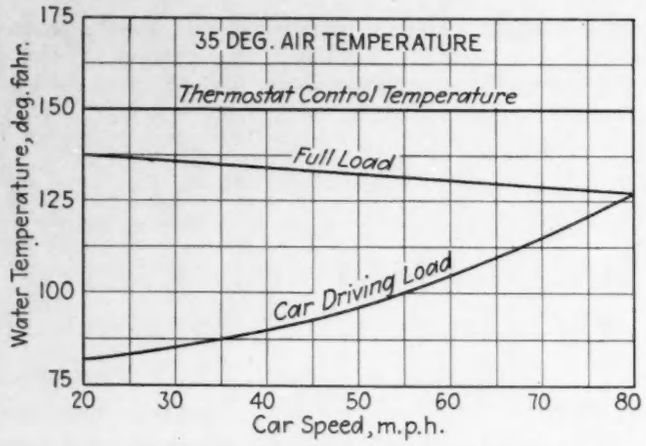


Fig. *B* – (Saunders Discussion) Cooling Curve at Various Speeds – Full Load and Car-Driving Load

a level road. The difference between these two curves, of course, being the power available for acceleration, hill climbing, and so on.

Fig. *B* shows a cooling curve at maximum horsepower at various speeds in m.p.h. together with a cooling curve obtained at car-driving load at various speeds in m.p.h., these figures being representative figures when running the machine in an air temperature of 35 deg. fahr. It will be noted that both the full-load curves and the car-driving-load curves are below the control temperature selected, namely, 150 deg. fahr. in both instances. These actual temperatures shown are temperatures that will be obtained with the particular cooling system under question which has sufficient capacity to permit the machine to run satisfactorily in an air temperature of 100 deg. fahr. at full load without boiling.

Without temperature control, at 20 m.p.h., the water temperature under the air conditions specified will be approximately 90 deg. fahr. and, to quote some comparative figures on metal temperatures which were run a number of years ago on an engine at 1000 r.p.m., under these conditions the hottest point of the engine, that is, the exhaust-valve seat, will not be in excess of 200 deg. fahr., and the coldest point is on the cylinder-wall on the non-valve side of an L-head engine, the temperature here being approximately 80 deg. fahr. The cylinder barrel itself will be approximately 145 to 150 deg. fahr. and, under these conditions, scuffing of the pistons probably will occur and crankcase dilution may be excessive.

In addition to these difficulties, due to the tremendous temperature difference existing under these conditions as compared with those existing under normal conditions, considering the flame temperature inside the cylinder compared to the water temperature on the jacket side, the heat input to the jacket with this low temperature will be much higher than that obtained normally, resulting in unsatisfactory operation as far as power is concerned, coupled with excessive fuel consumption. On the other hand, assuming a thermostat control temperature of 150 deg. fahr., the temperatures previously cited at various sections of the water jacket, combustion spaces, and so on, will each increase almost in direct ratio to the change in water-outlet temperature.

Now as regards the actual operation of the controlling apparatus, the hand-controlled shutters have their place in the sun, principally because of their economy of installation. However, it is extremely difficult to try to outguess what the engine is going to do next or what type of topography may be expected just around the corner so far as the road elevation is concerned. On this score, of course, the thermostatically controlled shutter is by far the more desirable, providing that the installation is a good one and the shutters are balanced reasonably so that the wind pressure at high speeds will not blow them open and so reduce the water temperature. The start-to-open temperature, the fully open temperature, the start-to-close temperature, and the fully closed temperature, should respectively not have lag of more than 5 deg. in each of the two major positions.

We had one experimental thermostatically controlled shutter installation where the start-to-open temperature was 140 deg. fahr., the fully opened temperature 150 deg. fahr., the start-to-close temperature 120 deg. fahr., and the fully closed temperature 70 deg. fahr. Needless to say, this was a very deplorable condition, and ways and means were found in the production design and installation to make a much better job.

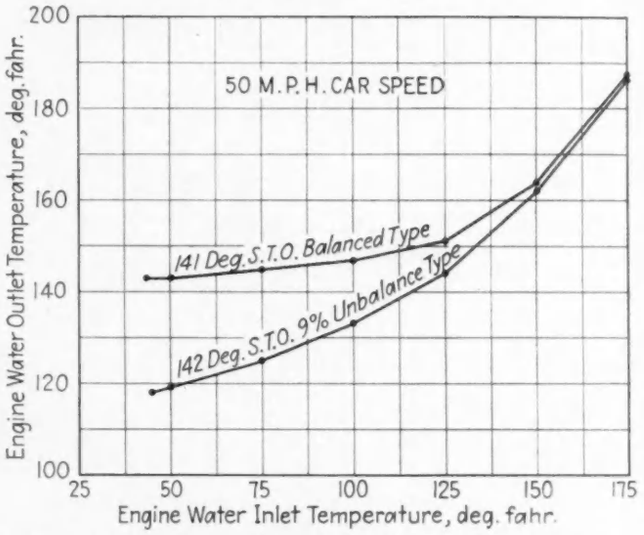


Fig. *D* – (Saunders Discussion) Effect of Water-Inlet Temperature on Thermostat-Control Temperature – Balanced and Unbalanced Types

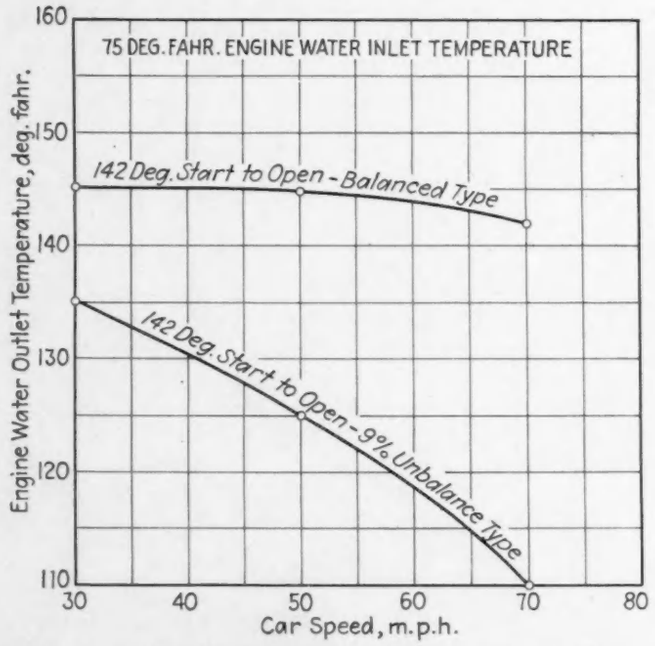


Fig. *C* – (Saunders Discussion) Balanced and Unbalanced Control Temperatures at Various Speeds

The majority of temperature-control installations on the market today are thermostats of the blocking type and, in general, these come under two headings, the balanced and the unbalanced type. The balanced type is best described as a unit in which the area of the valve head is equivalent to the area of the bellows head, the water pressure on one surface being offset by the pressure on the other. In this manner pump pressures will not materially affect the operation, and the liquid in the thermostat will be the element of control.

Some curves are shown graphically illustrating conditions that exist under these two conditions. These curves are self-explanatory. Fig. *C* shows the control temperature of the balanced type at various speeds in m.p.h. as compared to the type of control obtained with a thermostat having 9 per cent unbalance. In the first case, it will be seen that the water temperature does not vary more than approximately 3 deg. fahr. whereas, on the unbalanced type, the water temperature varies from 135 deg. fahr. at 30 m.p.h. to 110 deg. fahr. at 70 m.p.h. Of course, under these conditions the carburetor setting has to be on the rich side to take care of the operation of the car under the coldest water conditions.

Fig. *D* illustrates graphically how the water temperature inlet to the pump affects the thermostat control temperature, this temperature not being reached on the unbalanced type until an inlet temperature of 125 deg. fahr. is available, the balanced type maintaining the control temperature below 50 deg. fahr.

Fig. *E* shows the effect of water pressure in the block on the operation of the two types of thermostats. It will be noted that, with the balanced type, a change in water jacket pressure of from 5 to 10 lb. per sq. in., changes the leak capacity of the thermostat from 3 to 8

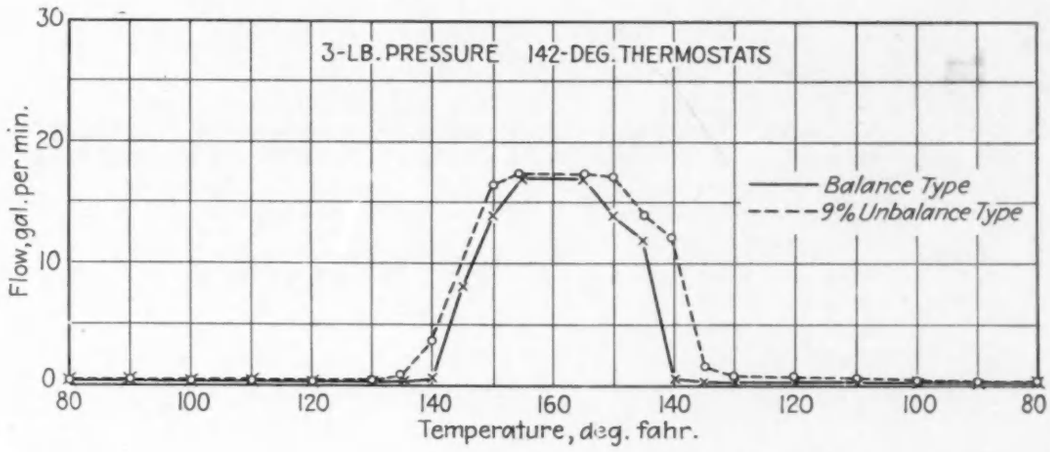


Fig. *F* – (Saunders Discussion) Thermostat Pressure Flow Test – Temperature Vs. Flow for Balanced and Unbalanced Types Set for 142 Deg. Fahr. at 3 Lb. per Sq. In.

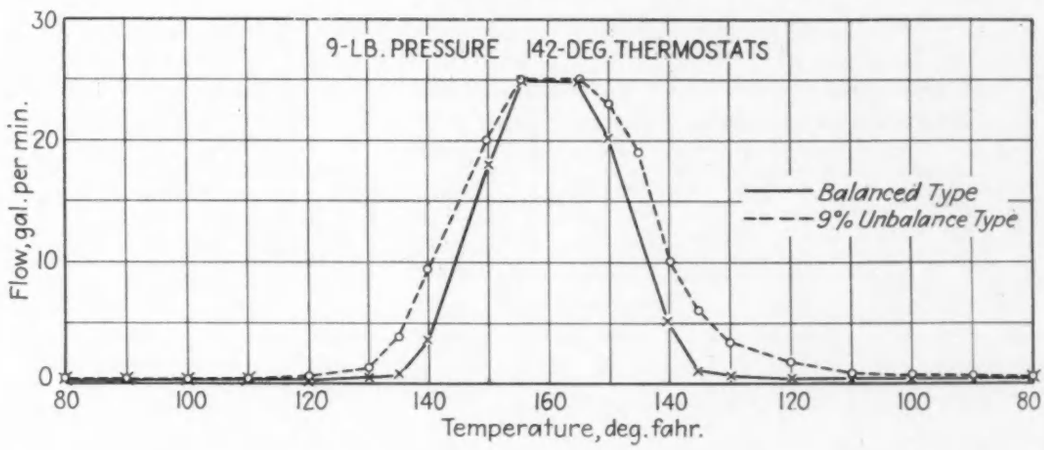


Fig. *G* – (Saunders Discussion) Thermostat Pressure Flow Test – Temperature Vs. Flow for Balanced and Unbalanced Types Set for 142 Deg. Fahr. at 9 Lb. per Sq. In.

gal. per min., whereas the unbalanced stat under the same conditions has a leak ranging from 7½ gal. per min. at 5 lb. per sq. in. pressure to 23½ gal. per min. at 10 lb. per sq. in. pressure, indicating that the unbalanced stat is not doing a good control job.

Again in Fig. *F* will be noted the difference in the type of temperature control of the two types of thermostats, the start-to-open, fully open, start-to-close, and fully closed figures showing the close control that is obtained with the balanced type. The unbalanced type again will be noted to vary quite appreciably at the various points, this particular test showing the performance at 3 lb. per sq. in. jacket pressure.

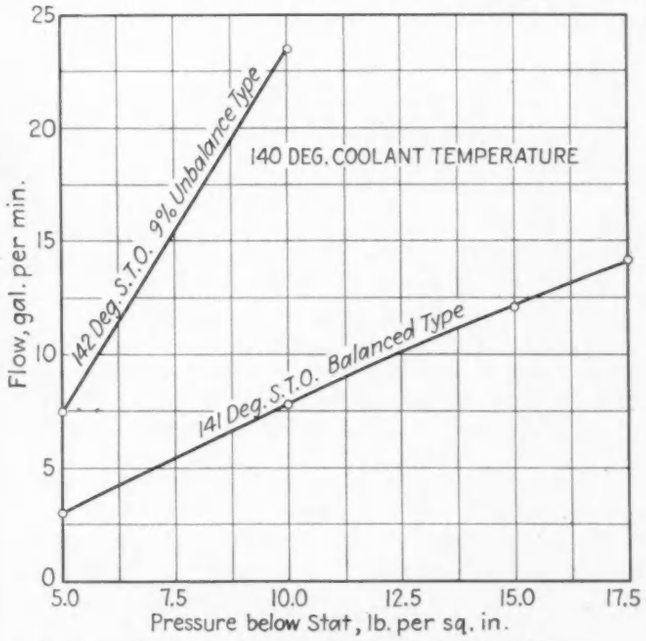

140 DEG. COOLANT TEMPERATURE
142 Deg. S.T.O. 9% Unbalance Type
141 Deg. S.T.O. Balanced Type
Flow, gal. per min.
Pressure below Stat, lb. per sq. in.

Fig. *E* – (Saunders Discussion) Effect of Water Pressure on the Operation of Balanced and Unbalanced Thermostats

On Fig. *G* we have a similar condition, however, the pressure has been raised to 9 lb. per sq. in. Again you will see that the balanced stat has much better control than the unbalanced. The change between the last curve and this one in start-to-open temperature is that, where previously at 3 lb. per sq. in. the temperature was 140 deg. fahr., under these conditions it is now 135 deg. fahr. whereas, with the unbalanced stat, the start-to-open temperature was 130 deg. fahr., and it is now less than 120 deg. fahr. The same characteristics of balanced versus unbalanced stats are applicable for both blocking and bypass systems.

The thermo-syphon system has fallen into universal disuse due to the inefficiency of the radiator operating with gravity circulation, the large volume of water with its attendant excess weight, and the anti-freeze problems attendant with this system for large installations.

The evaporative systems have their pros and cons and eventually may be adopted providing there is sufficient interest exhibited for further research work.

Concerning the rate of temperature rise, this figure is absolutely a function of the load and speed, the quantity of iron in the cylinder-block, and the volume of water. It is not possible to set down any hard-and-fast rule that will cover all cases, however, it is desirable to have a balanced type of thermostat with a minimum leakage. Fig. 43 of my article "Radiator Development and Car Cooling," S.A.E. TRANSACTIONS, December, 1936, page 511, illustrates in a general manner the effect of the location on a blocking-type thermostat, and it will be seen from this plate that it is highly desirable to put the thermostat directly in the cylinder-head for the most accurate control.

Concerning various types of automatic devices for cutting out fans, and so on, we have yet to find one that is satisfactory both thermally and mechanically. Although a great many attempts have been made to use the fronts of automobiles for small kinds of free advertising, unfortunately, although the advertising may be excellent, the temperature control is exceptionally poor.

As regards all the detrimental engine effects that arise from improper temperature control, there are other authors who in the past have prepared excellent papers describing various devices such as crankcase ventilation, and so on, who are much more competent than I to give you authentic information as to just how far-reaching these ill effects are.

The Chassisless or Unit-Car Question

By Stanley E. Knauss

Motor Coach Division, Gar Wood Industries, Inc.

THE experience gained over a period of many years in the development of light-weight, high-strength structures is now finding its way into the bus industry.

Investigation of present-day bus operations showed the need for a road vehicle that would carry the greatest possible payload of passengers with a smaller horsepower engine without dragging along a load of dead weight and useless structure that would eat up gasoline instead of miles.

A motor coach is now available in which are incorporated aircraft materials, design, and construction features resulting in a vehicle that is approximately 1000 lb. lighter than the lightest conventional design with the same engine horsepower and seating accommodations.

Motor-bus operators today can reduce costs by the use of light-weight equipment provided there is no sacrifice of strength and reliability. They must also meet the ever-increasing demands of the public for quietness, comfort, absence of vibration and engine odors – all of which can be accomplished by placing the engine in the rear which automatically gives a better distribution of weight than has heretofore been possible with the front-engine design.

TODAY, more than ever before, the bus operator requires a type of coach that will not only permit a lower operating cost but which, by appearance, design and construction, will produce a passenger comfort approximating that of a motor car.

The intercity operator is faced with the ever-increasing competition of lower railroad fares and more comfortable railroad day coaches. The transit operator is faced with a constant demand for a decrease in fare, and both classes of operators see steadily rising costs of fuel, material, and labor with little or no chance of raising their fares. The only hope, therefore, for increased profit lies in the use of a coach of lower operating cost and higher passenger appeal.

The coach I am about to describe was designed with these two fundamental ideas. It was conceived by a man – William B. Stout – whose accomplishments in the aeronautical field are known to all. It was engineered by aircraft men, and manufactured by a shop personnel who were trained in airplane factories. No one connected with the conception, design, or manufacture of the first experimental coach had any previous connection with the bus-manufacturing or bus-operating industry. It is only natural that, because of these facts, the coach produced would be of light weight since light weight is so extremely important in all types of aircraft.

In the early development of this coach it was quickly determined by the designer that, if light weight was to be secured, aircraft materials must be used. As a result, steel tubing was selected for the entire structural framework – a unit structure without the conventional chassis frame.

If the passengers were to experience greater comfort, the engine had to be placed somewhere else than in the front so that vibration, noise, odors, heat, and so on, would not be transmitted into the coach; consequently, the engine was installed in the rear. If riding comfort were to be had, the springs used on a truck chassis would have to be discarded, and special springs used to fit the conditions – otherwise a truck ride would result.

With these fundamentals determined, the coach was built in a weight of less than 6500 lb. with a seating capacity of 24 passengers, and turned over to various operators in order that experience could be had with the experimental model through actual daily service. Late last Spring, the coach was slightly redesigned to facilitate production.

The material used in the framework is, for the most part, 1¼-in. square welded tubing. A small amount of round tubing is used at the front and rear ends where double curves appear to facilitate the installation of the outside metal covering. All frame joints are welded – there being no screws, rivets, bolts, wood, or any other metal in the entire structural assembly.

The outside metal covering for the sides, roof, and bottom is of 22-gage body steel, and is installed with self-threading screws, making replacements of damaged panels a very simple job.

The frame unit complete weighs approximately 745 lb. without doors, and the steel and aluminum covering approximately 750 lb. Another 750 lb. is required for the plywood

[This paper was presented at the Annual Meeting of the Society, Detroit, Mich., Jan. 13, 1937.]

floor, linoleum, inside walls, head lining, molding, and insulation material.

Due to the light weight of the coach, it is possible to use the smaller mass-production powerplants, axles, and transmissions and clutches, so many thousands of which are in daily use in truck service around the country. The advantages of this arrangement are many. In the first place, it produces a gasoline economy heretofore not reached by previous coaches. Parts for these mass-production truck engines are available in practically every city in the country, thereby eliminating a costly department of the average bus operator – the stock room. The total light weight of the coach permits the use of smaller tires – a further reduction in cost – and also brings the coach lower to the ground, despite the fact that there is 79½ in. of head room from the depressed aisle to the ceiling.

Ten years ago the production problems in welding a tubular framework of this size would have been considerable but, with the strides made in the last few years in the art of welding, it now seems almost impossible for a man with the slightest welding experience to make a poor weld.

The sales problem in connection with this coach is unique. Operators who realize that the saving of a few cents a mile is the difference between a deficit and a profit are quick to see the advantages of light weight with its attendant lower costs and, almost over night, divorce themselves from previous ideas of associating strength with mass weight. Other operators who do not take the time to study the newer developments or who by habit of many years have come to believe that the mounting of a body on a heavy chassis meant strength, look at the tube framework, shake their heads, and immediately say: "What will happen in the case of an accident?"

It seems to be an unwritten law that new structures are received by an industry with considerable skepticism which is not removed until the structure has been subjected to a serious accident. These coaches in the hands of operators have been involved in two major accidents, both of which demonstrated without any doubt the ability of a steel-tube structure to "take it."

In one such accident one of these coaches was hauled into the shop one Monday morning after a collision on one of the major highways near Detroit where the coach, while going at a speed of better than 60 m.p.h., struck a five-passenger sedan without lights that appeared suddenly from a side road. The driver stated that he did not have time to place his foot on the brake pedal, and the terrific impact knocked the motor car 75 ft. down the road, rolled it over three times, and killed the three occupants; while the coach did not leave the highway.

In an impact of this nature, the welded-tubular structure seems to absorb and localize the shock, which action accounts for the fact that, with the exception of the windshield and one of the side windshield glasses, not one other window in the coach was cracked, let alone broken. The impact was so great as to emboss the spare tire on the tire-cover door. The axle was bent almost in a knot, the tube structure at the front end was bent, and a few tubes were broken, but there the damage was localized; in fact, the main-entrance door immediately back of the windshield was in perfect alignment and could be opened and closed with a finger tip.

Officers of the company operating the coach involved made the statement that, had the engine been in the front, it would either have been in the driver's lap or in a corn field and that, had the coach been of the conventional design of a body on a chassis, the strains would have been transmitted through the chassis, distorting it and, in turn, distorting the body. Early in our experience in designing structures of this kind, it quickly became apparent that there was a big difference between strength and rigidity.

Although these coaches accommodate 24 seated passengers when the interior is fitted for a transit type of service, it is very frequently necessary during rush hours to carry a standee load of another 24, and the structure must be rigid enough to take a concentrated load particularly at the front end when the coach is traveling at a fair rate of speed and drops one wheel in a hole in the pavement. If our experience with this coach, and in similar structures which preceded it, teaches any lesson, we must conclude that strength is secured from materials and design, and not from mass weight – that it is possible to build a coach of this size and carrying capacity in a weight of less than 6500 lb.; and that such a structure will last indefinitely and be just as strong after years of service as it was the day it was new and rolled out through the factory door.

Experience has proved in the operation of a fleet of these coaches over a distance of several hundred thousand miles that, because of their light weight the tires, even in the size of 6.50-20 have a mileage of in excess of 60,000 miles per set; brake linings have frequently given better than 40,000 miles of service; and gasoline mileage is more than twice that of heavier coaches of equal seating capacity. The physical condition of the driver at the end of a day's run is not one of fatigue due to wheeling a heavy vehicle in traffic for eight or more hours.

Again due to the light weight, performance is stepped up nearer to motor-car proportions; acceleration and deceleration figures are greatly improved. Both of these items are of extreme importance as they permit the driver to make schedules without taking undue chances by running at maximum speeds because of being late at the point of departure

Forgings Vs. Castings in Aircraft Production

IT is granted that the forging process is limited to use where sufficient production may be obtained to amortize tooling costs.

The highest strength aluminum-alloy casting has an ultimate tensile strength of 42,000 lb. per sq. in., yield strength, 25,000 lb. per sq. in. and elongation of 12 per cent in 2 in. Compare these values with those of the best forging alloy with an ultimate tensile strength of 65,000 lb. per sq. in., yield strength of 50,000 lb. per sq. in. and elongation of 10 per cent in 2 in. Further, consider the requirements of the Army, Navy and Department of Commerce, that all castings shall show in the analysis a 100 per cent margin over their design load. These requirements reduce the allowable values for the castings to such an extent that the forgings seem to be indicated. This condition, however, is only true in those cases where cast sections could be reduced, yet not be so small as not to be readily forgeable. Under other considerations, of course, castings may have to be used due to their ability to be made in more intricate shapes.

Excerpt from the paper: "Designing for the Use of Aluminum-Alloy Forgings and Extrusions in Aircraft Production," by Howard D. Houghton, presented at the National Aircraft Production Meeting of the Society, Los Angeles, Calif., Oct. 16, 1936.

X-Rays and Gamma Rays– Their Industrial Application

By Tom A. Triplett
Triplett & Barton Metallurgical Analysis

THE X-ray spectrum readily adapts itself to problems in chemical analysis and crystal formation. It is effective on very minute particles which otherwise cannot be segregated. A permanent record is made, and the specimens may be used over and over again, as the X-ray is nondestructive.

As a means of inspection, X-ray clearly shows the interior of objects such as welding, castings, forgings, cold-worked metals, and so on. Inhomogeneities that are very slight in width and a fraction of one per cent in thickness are seen easily on a radiograph. Defects thus found may be eliminated summarily by checking various steps in production.

IN the examination of materials there have been, from time to time, new and better methods developed to eliminate defects more completely as well as to perfect methods of manufacturing.

The fact that, when designing parts, we make allowances over the maximum stress alone shows the need for these studies and examinations. Through each advancement in the study of materials the former standards are raised to a higher level.

X-ray is one of these relatively new means of inspection and study. Its greatest value is found when it is used in connection with, and not necessarily to eliminate, former test methods. By its use it is possible to eliminate many of the defects as well as to regulate and control various steps in processing. In general, it may be called upon to determine proper manufacturing technique, to insure consistency, and to make a distinction between metal or alloy commodities with satisfactory or unsatisfactory behavior. X-ray enables the observation of the interior for inhomogeneities. In the analysis of fine structure, X-ray goes far beyond the microscope, even down to the ultimate pattern of atoms in space. These studies may be accomplished by several different methods of using X-ray.

Before going further, perhaps it is well to stop and ask: "What is X-ray? By what methods is it produced, and how is it used for the study and examination of materials?"

Today, the term "X-ray" is a misnomer in that we do know what it is and how it works. However, since in its infancy, its nature was unknown, the definition "X" was applied, and the name has prevailed in this country as well as in others with the exception of Germany where, in honor of its discoverer, Roentgen, a native of Germany, the term Roentgen rays is applied. Briefly, X-rays are light waves of a very short wave length (the range lying between 0.06 Angstrom units, or even shorter, and 1019 Angstrom units) overlapping the ranges of both gamma rays and ultra-violet rays. Although seemingly of different properties and produced in greatly different ways, X-rays and light waves are identical in every respect with the exception of their length and maintain the same velocity of propagation. Since their wave lengths are much shorter, or their frequency is greater, X-rays may be expected to penetrate materials and be related to a finer subdivision of matter than is possible for light waves.

There has been developed successfully by Lucas[1] an ultra-violet microscope. However, even with this forward step, a limit is reached. X-rays are able to take the observer on to ultimate molecules and atoms, and even on to the universe within the atom.[2] It may truly be called the "microscope of the atom."

Although there are several methods of producing X-rays, the most practical and generally practised method is the deceleration of a fast-moving stream of electrons by impinging them upon a tungsten target. This purpose is accomplished by a high-voltage direct current being applied to an X-ray tube. Due to a limit of time, we will not go into the detailed designing data of an X-ray machine and its various accessories. It will be sufficient to say that Westinghouse, General Electric, Kelley Koett, and many other companies produce equipment for this work. Most of this equipment is designed for medical purposes and has been modified for industrial use. It has, in most cases, proved satisfactory. The writer has found it necessary in the past, because of various inadequacies of available equipment, to design and produce some of his own. In some cases, such as at Boulder Dam, it was necessary to rebuild the market equipment to satisfy the needs more completely.

[This paper was presented at the National Aircraft Production Meeting of the Society, Los Angeles, Calif., Oct. 16, 1936.]

[1] See Pamphlet 1576C, June, 1926, American Institute of Mining and Metallurgical Engineering: "Introduction of Ultra-Violet Metallography," by F. F. Lucas, followed by several later publications.

[2] For information of the Beck-Bernard microscope, see *Journal of Royal Society of Arts*, Aug. 21, 1931, Vol. 79, p. 887; "Some Recent Developments in Microscopy," by L. C. Martin; also see *Journal of Experimental Medicine*, 1931, Vol. 54, p. 449, by Wyckoff and Ter Louw.

The question is asked: "How is X-ray used in the study and examination of metals and alloys?" The explanation lies under three general headings: (I) chemical analysis from X-ray spectra, (II) crystal diffraction by X-ray, and (III) radiography.

Under the X-ray analysis there may be listed several advantages, as well as some disadvantages:

(A) The advantages over chemical analysis are:

(1) Analysis of rare earths or metals where separations are difficult, if not indeed impossible.

(2) Extremely minute amounts may be identified, for example, the triumph of X-ray in the discovery of elements 72, 43, 75, 61, and 87[3].

(3) Greater safety since no reaction is involved, resulting in less work and in a saving of time.

(4) Material is used in any available form without loss, and thus the method is valuable for very rare metals, gems, and so on.

(5) Because a permanent record is kept.

(6) It is largely independent of the personal equation.

(B) The advantages over optical spectroscopy are:

(1) Simplicity of X-ray spectra as compared to the baffling complexity of optical spectra.

(2) Absolute independence of X-ray spectra from valence or chemical combinations. (Since only atoms and not smaller divisions of structure are involved, optical spectra are affected by the presence of foreign substances, the band spectra of molecules, as well as the kind of chemical combination involved.)

(C) The disadvantages of X-ray as compared with chemical and optical analysis are:

(1) Equipment is difficult to obtain, somewhat expensive, and requires special technique for accurate qualitative analysis.

(2) It requires comparison of line intensities with standards for positive identification.

(3) Intensities depend upon the particle size of the substance being analyzed.

(4) Since characteristic wave lengths cannot be measured by usual crystal gratings in the lighter elements, the practical limit is calcium.

(5) Somewhat inaccurate results may be found by volatilization of focal-spot-target material in the primary emission method. This difficulty can be overcome partially by presenting fresh anode surface or by using the fluorescent-spectra methods which involve prolongation of time because of lessened intensity.

(6) There is selective filtration on absorption edges of emission lines constituting the mixture. (These difficulties can be avoided when standardizing substances are registered on the same photographic plate.)

(7) Blank runs of apparatus are needed to check appearance of foreign lines inherent to the equipment.

(8) In some cases there is a resonant radiation of the characteristic rays of one element with that of another, causing a strengthening of the intensities of lines for the latter.

(9) The effect of the absorption edges of silver and bromine in the film used.

(10) The varying sensitivity of photographic emulsion to different frequencies.

Crystallography is now built up to the conclusion, from careful and tedious observations with the optical goniometers and microscopes, that almost all true solids are crystals, either single entities with pairs of paralleled bounding surfaces arranged in definite geometrical fashion at measurable angles, or in aggregates of these crystals. All exterior appearances indicate some regular internal arrangement of unit building material. In the past, physicists were unable to determine points of useful contact with the applied science of geometric crystallography without experimental methods of investigational study and without a definite knowledge of the forces holding atoms and molecules together, as well as atomic and molecular structure conception.

Physicists have worked largely with gases and liquids because of their freedom of motion. Inasmuch as all directions are alike, it is possible to calculate with reasonable accuracy the very practical phenomena of behavior of gases and liquids by means of simple hypotheses.

Solids offer great complications due to the fact that the atoms and molecules are bound together tightly by their material forces. The surmise is that the exercise of these forces would tend to produce regularity of arrangement and, indeed, X-ray analysis has shown that such a regularity exists in practically every solid substance. A scientific knowledge of the ultimate structure of solids, which are crystals in natural state, is self-evident giving consideration to the definition of desired physical and chemical properties. Practical importance is shown in the lubricating properties of long-chain paraffins or graphite, the covering power of pigments, the stretching of rubber, the dielectric capacity of materials, the plasticity of lime, the wearing properties of case-hardened steel, the strength of steel girders as well as of alloy structures, the corrosion of aluminum alloys, and an indefinite number of other practical phenomena which depend upon ultimate crystalline structure. It has been shown clearly by Bragg that the only properties of solid bodies that are not relative in some manner to crystalline structure are those that depend upon atomic characteristics alone, such as weight. With few exceptions the mode of arrangement of the atoms and molecules of a solid substance determines in every aspect its behavior.

Perhaps, a clear statement relative to the ultimate crystalline structure of materials would be proper at this time. Quoting from Sir William Bragg, we find the three types of assemblage are:

"The simplest is that of the single atom as in helium in the gaseous state, in which the behavior of every atom is on the whole the same as the behavior of that of every other atom. The next is that of the molecule, the smallest portion of a liquid or a gas which has all the properties of the whole. And the last is the crystal unit, the smallest portion of the crystal (really the simplest form of a solid substance) that has all the properties of the crystal. There are atoms of silicon and oxygen; there is a molecule of silicon dioxide; and a crystal unit of quartz containing three molecules of silicon dioxide. The separate atoms of silicon and oxygen are not silicon dioxide, of course, in the same way that the molecule of silicon dioxide is not quartz; the crystal unit consisting of three molecules arranged in a particular way is quartz."

Without going into the mechanics of crystal diffraction by X-ray, the aim is to determine arrangement of atoms and molecules in a crystal unit as well as to account for properties in terms of that arrangement in the crystal, thus allowing one to determine whether a structure is:

(1) Crystalline or non-crystalline.

(2) Crystallographic system, including space group, unit-cell dimensions, parameters of atoms and molecules, and so

[3] Atomic number: 72, hafnium; 43, masurium; 75, rhenium; 61, illinium; 87, virginium.

on, deduction of crystalline unit (molecule, ion, or atom) of size of unit, type of binding, and general properties to expect.

(3) Chemical identity, including crystalline changes and stability.

(4) Allotropic modifications.

(5) Single crystal or aggregate thereof.

(6) Crystal orientation of single crystal or of grains in the aggregate.

(7) Alloy formation – type and mechanism.

(8) Fibered or random aggregate, including relative degree of preferred orientation in different stages.

(9) Grain size, particularly in colloidal range.

(10) Analysis of heat-treatment.

(11) Grain-growth control and mechanism of re-crystallization as well as the establishment of correct annealing technique.

(12) Internal strain or distortion.

(13) Differentiation between interior structure and surface structure.

(14) Extent of deformation as well as mechanism of fabrication in drawing, rolling, and so on.

Industrial Radiography

Any material may be radiographed to determine its gross structure and the presence of defects within that structure. This operation is done by means of the differential absorption of penetrating X-rays, and in a way that is non-destructive to the object being radiographed. These inhomogeneities may be recorded on either the photographic or fluorescent screen. For the purposes of examining metals, the writer has found that the photographic film has advantages over the fluorescent screen in that it keeps a permanent record for future reference. Moreover, the film, being very sensitive, shows an increasing percentage of defects and, last, a greater thickness of material may be examined.

The fluorescent screen has one advantage – it is somewhat cheaper in production work. In our radiographic work, we have used various machines ranging from 100 kv. to 600 kv., and we use frequently for heavier sections of steel the penetrating gamma rays emanated from radium. The relatively simple technique is the same for both methods. A radiograph may be considered as a shadowgraph which, due to the differential absorptive properties of materials, will record on a photographic film the interior structure much in the same manner as a shadow is cast on a screen.

In their action on sensitized film, X-rays are similar to light, except X-rays affect throughout the whole thickness of the emulsion to gain speed. This greater layer is the major difference between ordinary film and film used for X-ray purposes.

In a review of the laws of exposing photographic film,

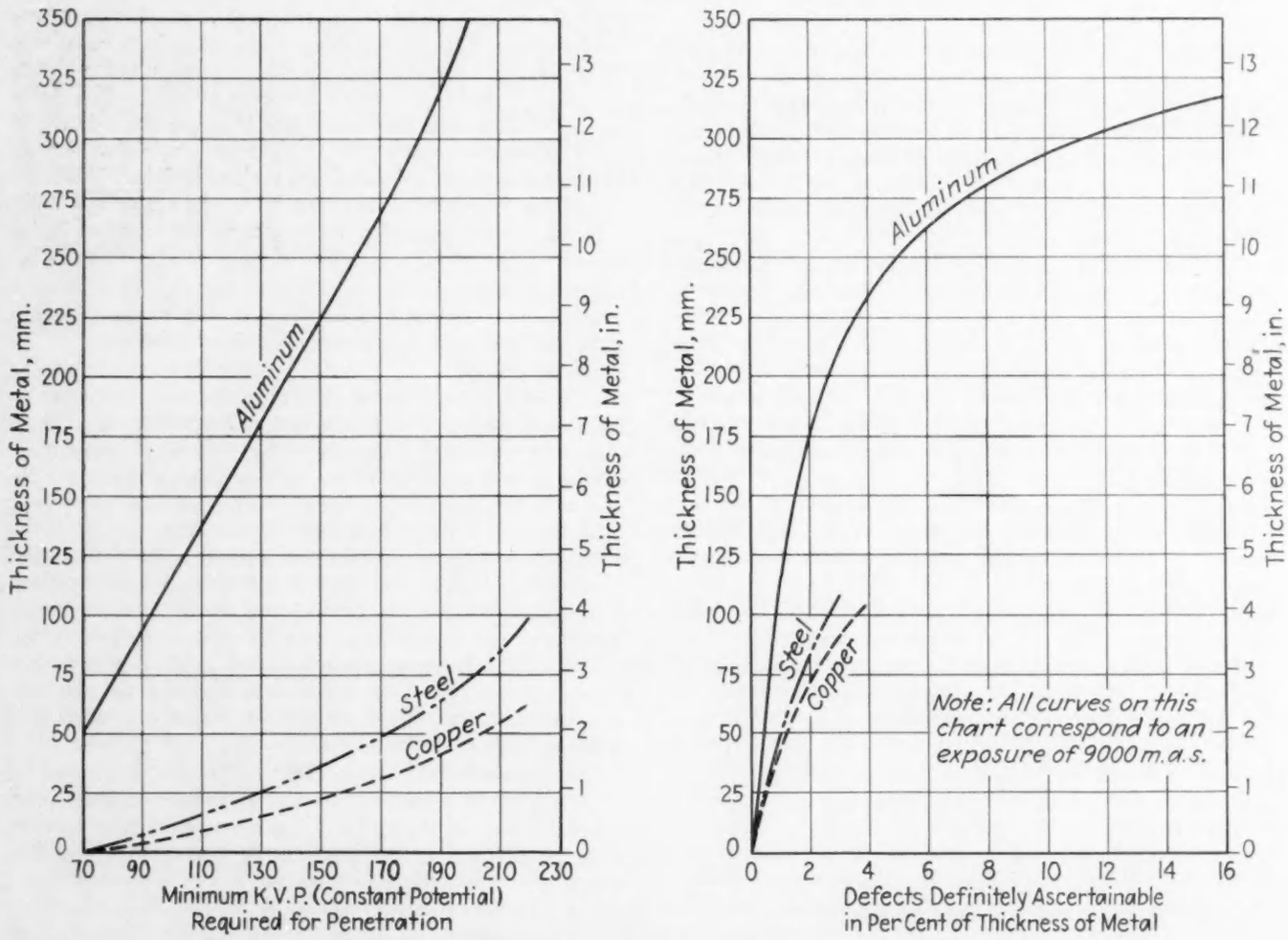

Thickness of Metal, mm.
Thickness of Metal, in.
Aluminum
Steel
Copper
Minimum K.V.P. (Constant Potential) Required for Penetration
Defects Definitely Ascertainable in Per Cent of Thickness of Metal
Note: All curves on this chart correspond to an exposure of 9000 m.a.s.

Fig. 1 – Results of Experiments with Steel, Copper, and Aluminum

the frequency and intensity, as well as the time of exposure of the incident rays, will be found the important factors. Apparently equal blackening results from equal energies absorbed regardless of wave length and, within a range, Bursen's law that equal products of time and intensity produce an equal blackening is authenticated. A greater photographic effect will be evident with high intensity for short duration, rather than with a longer exposure at a correspondingly smaller intensity. However, because of secondary radiation, it will be found that longer exposures with the lowest economical voltage will produce the most satisfactory radiograph.

Taking into account secondary radiation (sometimes called scattering) which limits the sharpness of delineation of clearly defined differences in thickness of material – which corresponds to defective areas – experiments for steel, copper, and aluminum give results as shown in Fig. 1. Although the chart shows a 2.7 per cent definition for steel at 100 mm., by using 400 kv., the American Manganese Steel Co. in its Chicago plant has been able to show a definite 2 per cent through a 5-in. section of steel. With gamma rays this percentage can be carried into even thicker sections of material.

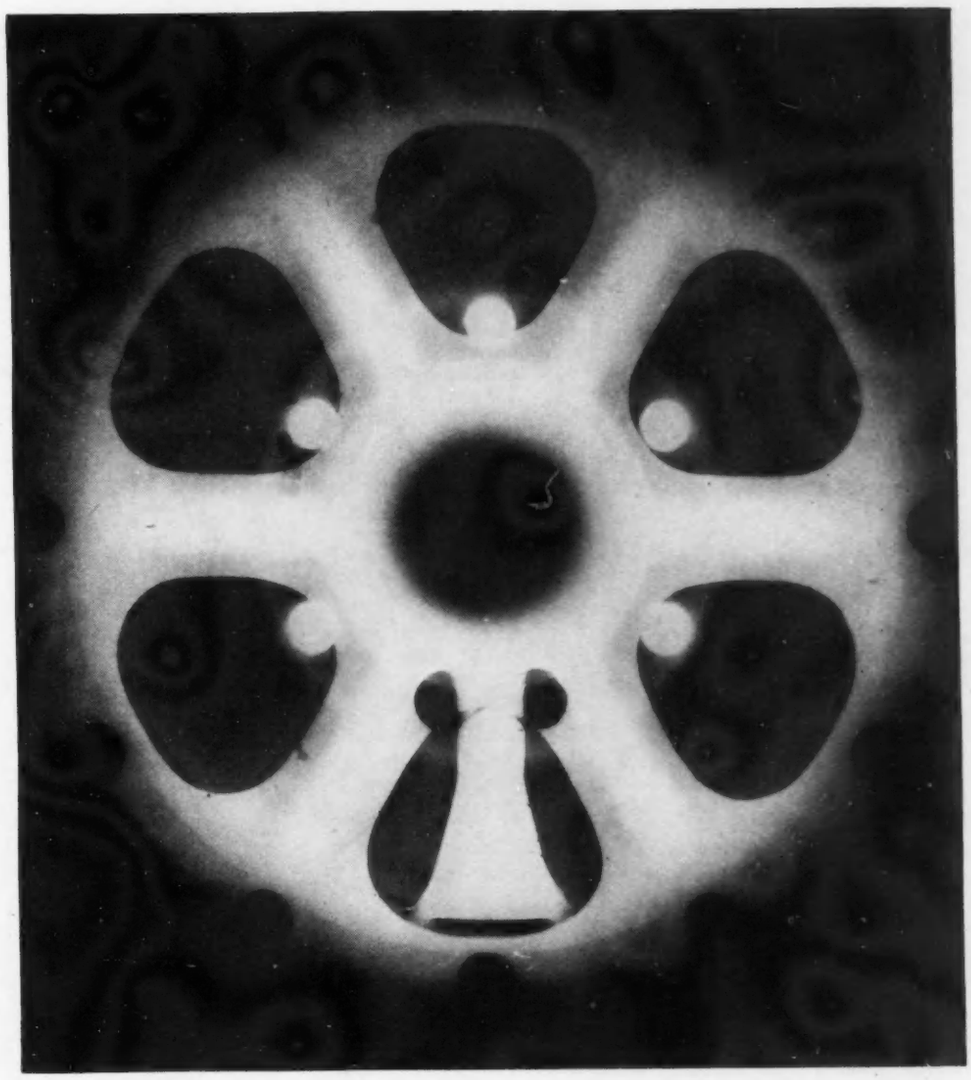


Fig. 2 – Motor Nose Casting Showing Effects of Poor Foundry Technique Resulting in Numerous Blowholes, Cracks, and so on

These figures are consistent only with the same exposure factors, screens, and so on, and vary with different films, screen speeds, and kv.p. applied. When methods for reducing secondary rays, and/or when non-screen technique is used, the percentage of difference that can be found will be of a lesser magnitude.

Radiographic Applications

Perhaps the most important industrial application of the X-ray radiographic diagnosis is that of castings because of their wide usage and because of the uncertainty of gross structure. See Figs. 2 and 3. Although a diagnosis can be confirmed readily by incisions into castings, interior defects can be radiographically detected without, in any way, affecting or destroying the castings. Gas cavities, slag and sand, or other inclusions; shrinkage cavities, porosity, cracks, metal segregations, and oxidation in light alloys are clearly detected. In the past six months our group has made an examination of over 2000 castings, and has found castings ranging from very bad to practically perfect. Without making a definite survey of the actual percentages that were radiographically unacceptable, the figures indicate 20 per cent or more, depending upon the foundry and the materials.

Of these defects, perhaps shrinkage, cracks, and inclusions constituted the major portion although, in some of the high-strength light alloys, oxidation played an important role. We might state here that, in working with the source of supply of the aluminum castings, upon finding these various defects, it was able to revise foundry practice, gating, chilling, and other methods to eliminate the majority of the defects in the patterns that were radiographed.

Some of the other applications of radiography are inspection of weld material, examples of which are shown in Fig. 4; tubing used in aircraft construction (Fig. 5); testing of materials for corrosion, for example, aluminum (Fig. 6), steel, and especially cables; and the radiography of rolled sheet metal to determine the effect of either cold or hot work. We also have found that among the things that can be examined advantageously are forgings, propeller blades, and springs; in fact, the list is much too long to attempt making any classification, there being practically no limit to the applications for which beneficial inspection can be made. In the examination of propeller blades one finds immediately surface cracks that have escaped previous attention (see Fig. 7), as well as any defects in the interior.

Fig. 4 – Spotweld Test Specimens To Determine Spotweld Condition

In the development of the new Model 12 ship, the Lockheed Aircraft Corp. used X-ray on all their castings to facilitate foundry technique and to remove any doubt as to the condition of the castings and fittings in their ships. Much of our work is based on data compiled from this source.

From a standpoint of cost on a production basis, X-ray can be very economical when all factors are taken into consideration, such as the elimination of machine loss, time, and so on. As a rough estimate the cost will vary from a maximum of $2.00 per sq. ft. of film down to as low as perhaps $0.70 per sq. ft.

At this time, I am going to include condensed statements of some of the users of X-ray examination taken from published articles:

Iron Age, February, 1935. – The American Manganese Steel Co. states that both X-ray and gamma ray have become important tools to manufacturers who turn out products with a minimum of interior imperfections.

Marine Engineering, September, 1935. – M. M. Hutton indicates that welded joints, forgings, as well as castings and other items, are being radiographed to advantage in ship construction.

Iron Age, April 30, 1936.– Lieut. E. B. Perry, machinery superintendent, Philadelphia Navy Yard – A perfect casting may be had by X-ray or gamma-ray examination, and those not so good may be made so from the information obtained. It is to be stressed that the X-ray or gamma ray is only a tool with which a skilful operator may search out small defects or an unscrupulous or untrained operator could hide the most explaining defects.

Iron Age, Jan. 24, 1935. – Riveting Defects X-Rayed – A riveted structure should approximate the strength of a solid

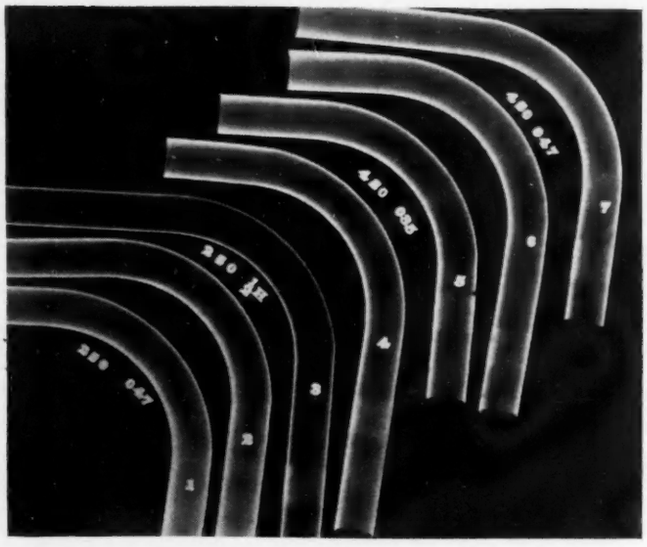


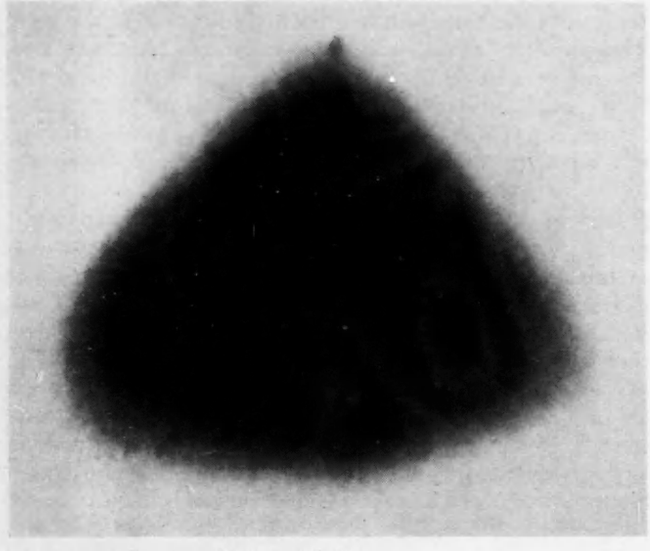
Fig. 5 – Study To Determine Minimum Bending Radii of Various Aluminum Tubing

material, and ill-fitted rivets are to be avoided in structures of vibratory stress.

Electrical World, April 13, 1935. – With X-ray the experienced radiographer can see into a casting to a depth of 5 in. and make sure that all defects within the area photographed will show clearly either shrinkage, spongy metal, blowholes, internal cracks, or inclusions and then, with this inside information and by a change or a series of changes checked by X-ray inspection, reach a designed solution.

Eastman Co.'s Photography Works for Industry. – F. C. Ellis states that the next decade will not be gentle with manufacturers whose products are sub-standard. The second outstanding recent recognition of X-ray was the inclusion of X-ray examination in the specifications of the welding done on the steel penstock at Boulder Dam.

Engineering News Record, Nov. 15, 1934. – It states that the X-ray method of testing welding at Boulder Dam was selected in preference to gamma ray because of greater economy in speed and better contrast. The writer, during his sojourn there, used both methods on this project, gamma rays being especially convenient where it was difficult to set up X-ray apparatus.



(Courtesy of Standard Oil Co. of Calif.)

Fig. 3 – Blowholes in a Welded-Steel Header Casting

(Courtesy Douglas Aircraft Co.)

Fig. 6 – Corrosion Study of Various Aluminum Alloys

1. 3S as standard
2. 17ST
2A. 17ST anodized
3. 17STAL
3A. 17STAL anodized
4. 24ST
4A. 24ST anodized
5. 24STAL
5A. 24STAL anodized
6. 52S
6A. 52S anodized
7. 53S
7A. 53S anodized

Metal Progress, Dec. 19, 1934. – Article by F. K. Ziegler and D. W. Bowland of Electro-Alloys Co., Elyria, O. – The company with which the writers are connected has adapted X-ray apparatus as an integral part of its inspection. They go on to state that service records on many castings that were subject to very careful visual inspection before shipment have proved conclusively that some forms of internal defects materially shorten their life, and proper use of X-ray would have undoubtedly located these defects. Also that the use of radiography for final inspection causes everyone in the foundry to take greater care and to use every precaution known to them to avoid any irregularities in the finished product.

Steel, Dec. 2, 1935. – Brooklyn high school installs X-ray equipment to teach industrial radiography – This school recognizes the need and future for this method of inspection in industry, and has installed this equipment to enable a training of operators for this purpose.

University of Illinois Engineering Experimental Station, Bulletin No. 193, July, 1929. – Albert Westman in his article on fire brick and X-ray states that, even with the best microscopic equipment, it is difficult to make an identification of fire brick gross whose diameter is smaller than about 100,000 Angstrom units. With X-ray, it is possible to attain patterns of particles with diameters as small as 50 Angstrom units or about 1/200,000th of the smallest particle suitable for petrographic work.

Scientific American, February, 1936. – Indicates a new method of testing by X-ray the lubricating qualities of oil.

Metal Progress. – Norman P. Goss, research department, Gold Metal Processes Co., advises that, in the study of preferred orientation and directional properties of sheet metal rolled in various ways, X-ray is indispensable, as well as in the study of grain structures at any given temperature.

Metal Progress, June, 1935. – Ziegler says that X-ray does things. It shows all defects that are slow to affect the life of alloy castings and is easily adaptable to irregular surfaces and sections. It differentiates sharply between defects of different characters and is the highest type of inspection yet developed for castings, giving beneficial results alike to customer and manufacturer.

Inquiry will bring a more complete list of articles and books on the subject of X-ray in industry.

At this time I want to thank especially the Lockheed Aircraft Corp., Douglas Aircraft Co., and Boeing Aircraft Co., for their permission to reproduce some of the fittings which we have taken for them and for the cooperation which they have shown in assisting us in our research work on this problem.

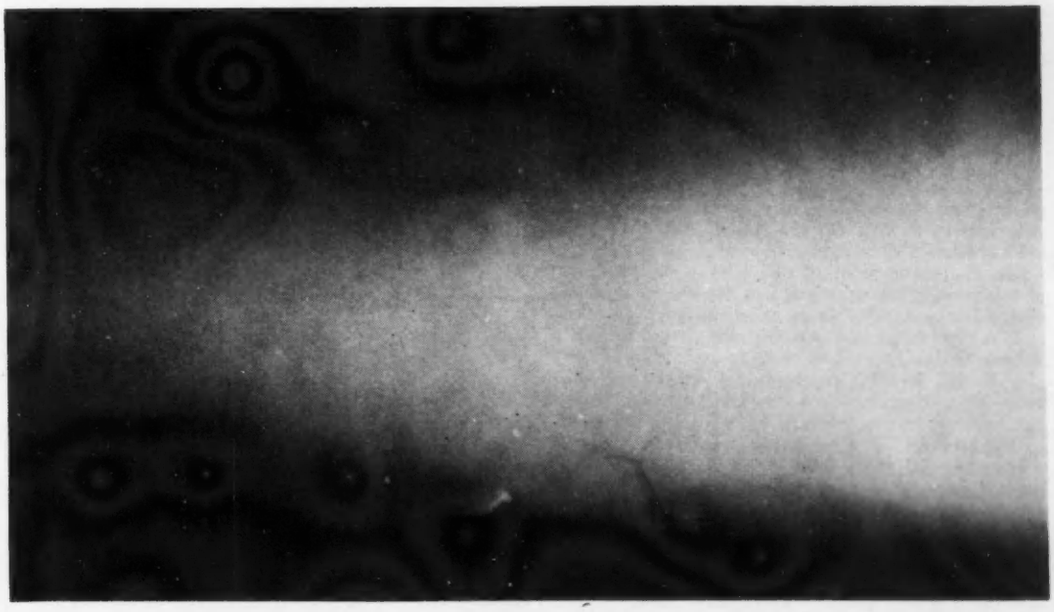


Fig. 7 – Crack off the Leading Edge of a Metal Propeller – the X-Ray Being Used To Determine the Extent of the Crack

Discussion

X-Ray Examination in Aircraft Manufacture

—Harvey Christen
Lockheed Aircraft Corp.

SINCE the inception of the Lockheed Electra, casting inspection prior to machine operation has been a tremendous problem. Chemical and physical analysis along with visual inspection had eliminated a small percentage of rejections prior to processing. It was only through actual machine operation that extreme porosity, slag inclusion, and shrinkage cracks were eliminated. The machine operation, as usual, was invariably within the last two or three operations, or approximately 80 per cent of machine time was before rejection occurred.

The result of machine-operation inspection was unbalanced and of extremely high cost in addition to serious production-schedule delay. Often a period of 10 to 30 days elapsed before a satisfactory casting could be obtained from the source of supply. The production program suffered accordingly with all possible work done toward a satisfactory substitution. There were many pattern changes as well as foundry-molding and processing-practice experiments before a satisfactory casting could be produced. Many castings were examined at the foundry by actual cutting away of the sections wherein the trouble appeared. This method oftentimes resulted in changes of foundry practice that usually produced a satisfactory casting in the end but with considerable delay.

Introduction of X-Ray into Our Inspection Routine.—In late 1935 we engaged in a contract involving the requirement of forgings where castings had been our standard practice. The contractor offered the alternative of using castings subjected to X-ray inspection which we accepted due to the prohibitive delay involved in obtaining forging dies. Thus originated the first adoption of X-ray to our routine inspection.

Actual Demonstrations of X-Ray Findings.—In the X-ray inspection of our castings the nature of the rejection is classified in three and sometimes four types. The most common type is porosity which, unless it exists to a high degree or of extremely large pores, is not considered worthy of complete rejection. The second type, known as slag or foreign-material inclusion, is watched very closely as a large grouping of slag has, in our experience, resulted in weakening of castings to the extent that breakage could occur easily in processing, or in actual service of the casting. The third type, commonly known as blowholes, is usually a direct result of foundry practice. The extent and size are not known, except by accidental appearance at the machine surface, other than by X-ray. The fourth type, generally known as material separation or shrinkage cracks, is the most dangerous. The cause of this type of rejection is usually found in design, pattern, and possibly, molding practice.

A good example of modification in design can be shown by our robot elevator mast located at the cockpit control column. The original design from all outward appearances was entirely satisfactory. Upon examination by X-ray, a shrinkage crack was found at the adjoining of the cable-attachment boss to the flat web of the casting. The first step, which was logical, was the use of larger fillets to afford a less rapid change of section. The pattern was rushed to the foundry for replacement castings which were received in record time. Further X-ray examination showed the shrinkage crack still remaining. Apparently the increase of fillet radius was not satisfactory. Immediate study was made and, as a result, the foundry was instructed to add additional metal tapering from the boss into the web in a fan-shaped design. This last correction resulted in a perfect casting.

We have experienced considerable difficulty with a casting installed in our landing gear, known to us as a trunnion. The nature of the design and the type of alloy used were a combination that resulted in continuous grief. We actually had breakage in the field, but fortunately the time and extent of failure did not cause damage to any part of the landing gear or ship. It is definitely known that the failure of this casting did cause delay in schedule for the operator. Immediately upon failure of this casting a modification of design was made increasing the wall thickness to nearly double its original size. Also X-ray inspection was used in every casting for replacement in the field and for production. This method resulted in the finding of inferior castings due to the nature of the alloy with which they were cast and due to what we believe to be incorrect foundry practice. Due to the extremely hard service to which these castings are subjected, we have found it necessary to change the alloy in addition to the foregoing X-ray inspection.

Our Lockheed Model 12 has had every casting X-rayed in the first ship to make necessary correction of design and check on foundry practice. Each design was X-rayed continuously until design and foundry technique were altered resulting in satisfactory castings. We found it necessary to establish our X-ray inspection service in the immediate vicinity of our casting source to eliminate all possible cost in delay and the return of defective castings.

We have used X-ray inspection of welded joints and brake shoes in which we have encountered serious trouble. In all cases we arrived at satisfactory correction of difficulties and of production delay. It is our plan to continue the practice of X-ray inspection of all new casting designs until a satisfactory casting can be obtained where rejection is believed to be direct cause of design. I also can state that the result of our inspection along with the cooperation of our source of supply is that only one aluminum-alloy casting was rejected in the last four months due to poor foundry practice. This rejection was found by machine operation. The nature of the defect was inclusion of a hard metal which could not be touched by a high-speed cutter. The nature of the material is at present unknown.

It is my belief that the benefits of the foregoing X-ray inspection examples are the direct results of the untiring efforts to produce more-perfect castings by the source of supply, the X-ray laboratories, and the aircraft inspection department. I am certain that, with the use of X-ray inspection, casting failure due to defects in themselves will be reduced to a minimum.

Will X-Ray Widen Use of Steel Castings?

—Wilbur G. Wood
Douglas Aircraft Co.

IN the design of large airplanes there is a trend toward the use of steel castings for fittings that are subjected to high loads. Under most design conditions encountered, steel castings could be used to advantage over the present types of fittings if certain obstacles could be overcome. To what extent can the use of X-rays help to solve these difficulties?

If aluminum-alloy castings were replaced by steel castings heat-treated to 150,000 lb. per sq. in. tensile strength, it would result in a reduction of weight, an increase in yield strength, and an increase in fatigue endurance limit. The difficulty is in obtaining castings free from blowholes.

If welded-steel construction were replaced by steel castings with suitable heat-treatment, it would result in lower costs of manufacture and greater reliability. The difficulty is that large castings with the thin webs and flanges required are subject to shrinkage cracks and poor grain structure due to high pouring temperatures.

If steel forgings were replaced by steel castings, it would result in reduced costs and greater flexibility of design. The difficulties here are in obtaining castings free from all defects and the fact that, at the present time, castings are penalized by the requirement of a margin of safety of 100 per cent.

If aluminum-alloy forgings were replaced by steel castings heat-treated to 180,000 lb. per sq. in., it would result in reduced cost, increased yield strength, and increased fatigue endurance limit. The difficulty, in addition to the ones just mentioned, is the accurate control of the high heat-treatment to insure the desired physical properties and still leave the material machinable.

Reports X-Ray Successful for Inspecting Castings

—James Gerschler
Assistant Chief Engineer, Lockheed Aircraft Corp.

MR. TRIPLETT'S paper has been very interesting and brought out the fact that the X-ray method of inspecting castings is quite reliable.

We have found that, since we have used the X-ray for inspection work, the technique, workmanship, and material itself in the castings, have been improved greatly.

At the present time we design castings with a 100 per cent margin of safety over the design load. This margin is required by the Bureau of Air Commerce to take care of miscellaneous variations. In the case of Dural it is often necessary to design castings that are somewhat out of proportion due to this fact. I would like to know if Mr. Triplett thinks that, as X-ray technique develops, whether it would be practical and safe to reduce this 100 per cent margin of safety now required.